ACME

Advanced Combustion via Microgravity Experiments

SCIENCE REQUIREMENTS

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(CLD Flame)

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Electric-Field Effects on Laminar
Diffusion Flames (E-FIELD Flames)

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Advanced Combustion via Microgravity Experiments

Four gaseous fuel experiments

(1) CLD Flame	**Long & Smooke (Yale U.)**
(2) E-FIELD Flames	**Dunn-Rankin (UC Irvine) et al.**
(3) Flame Design	**Axelbaum (Washington U. in St. Louis) et al.**
(4) s-Flame	**Law (Princeton U.) et al.**

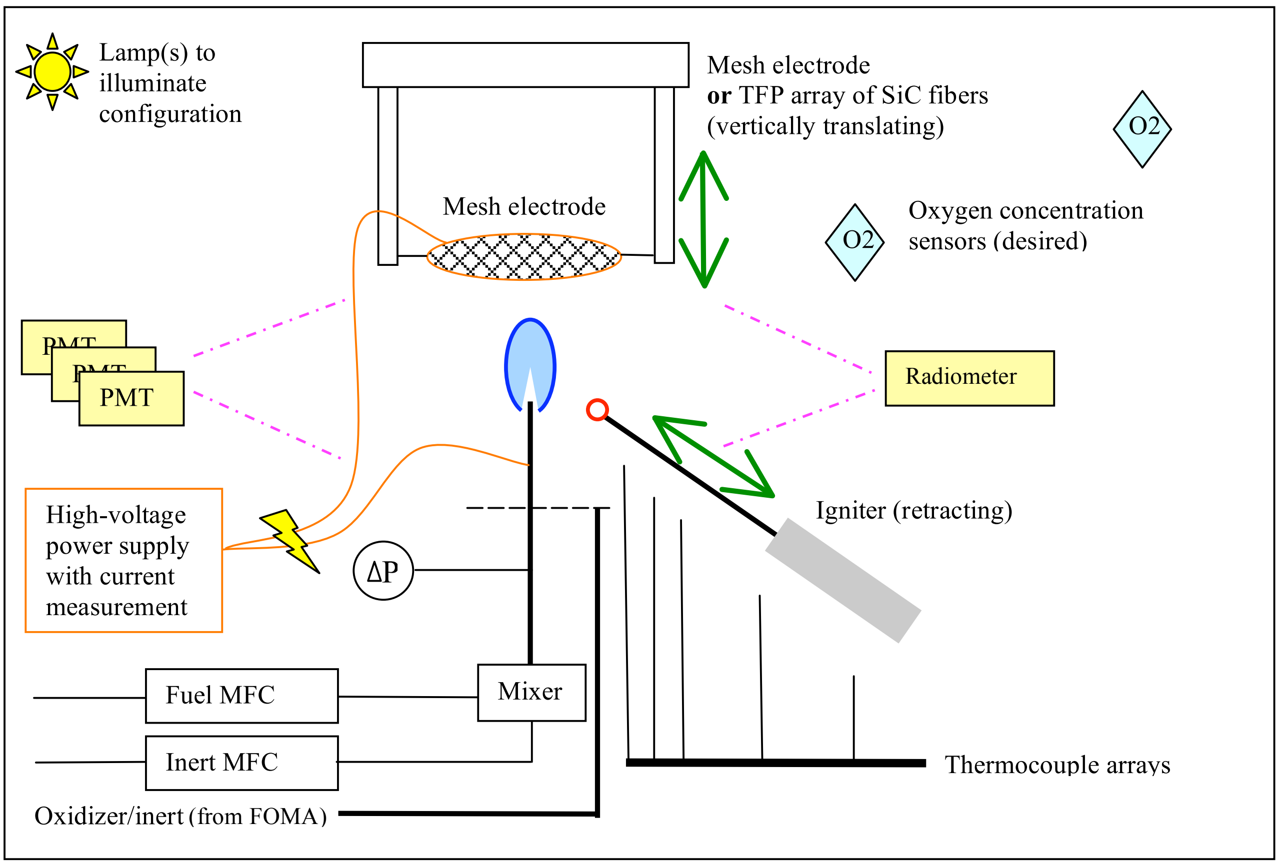

Figure 1. ACME insert concept, showing the study of electric field effects on a gas-jet flame.

Tracked changes in this document (in MS Word) are relative to the 2009-01-02 version.

ACME Hardware Concept

The ACME-specific hardware consists primarily of an insert for the Combustion Integrated Rack (CIR), an avionics box (potentially based on the MDCA design), and gas bottles for use with the FOMA. The principal components mounted on the modular insert are shown in Figure 1 and are listed below.

1. exchangeable burner
2. gas delivery system for burner (supplemental to the FOMA)
3. retracting igniter (potentially specific to the burner)
4. high-voltage power supply and mesh electrode
5. lamp for reference images of the experiment configuration
6. translating thin-filament array for pyrometry in soot-free flames
   (tentatively removed with installation of the mesh electrode)
7. various sensors for:
   7.1. temperature
   7.2. flame radiation and chemiluminescence
   7.3. oxygen concentration
   7.4. ion current and electric potential for study of electric field effects

There are three types of gas-fueled burners for the first set of ACME experiments:

porous spherical burner
gas-jet burner
axisymmetric coflow burner.

Requirement Sources

The primary sources for requirements are identified with superscripts as follows:

1	CLD Flame
2	E-FIELD Flames
3	Flame Design
4	s-Flame
*	Project Scientist, often reflecting general requirements
<#	Experiment #, but relaxed or altered by Project Scientist
>#	Requirement is more demanding than experiment #

Science Data End Products (SDEPs) corresponding to various science diagnostics are listed by the number-letter-number sequence below:

Experiment (number, see above)
Objective (letter)
SDEP (number)

An SDEP may be listed under any diagnostic that can provide at least some of the needed result. SDEPs are not listed for monitoring measurement of independent variables (e.g., flow rate).

Nomenclature

1g	normal (Earth) gravity
A	amp, amplitude
ACME	Advanced Combustion via Microgravity Experiments
atm	atmosphere
C	Celsius
CIR	Combustion Integrated Rack (CIR)
cm	centimeter
FEANICS	Flow Enclosure Accommodating Novel Investigations in Combustion of Solids
fps	frames per second (for imaging requirements)
FWHM	Full Width at Half Maximum (measurement of the spectral width of a bandpass filter)
g	Earth gravity (9.8 m/s^2)
GC	gas chromatograph
HiBMS	High Bit-depth Multi-Spectral (camera for CIR)
HV	High Voltage
Hz	Hertz (unit of frequency equivalent to 1/second)
IR	infrared
ISS	International Space Station
Hz	Hertz
K	Kelvin
kV	kilovolt
MAMS	Microgravity Acceleration Measurement System
MFC	mass flow controller
min	minute
mm	millimeter
ms	millisecond
nozzle	gas-jet burner or central/core tube in coflow burner
PaRIS	Passive Rack Isolation System (with which CIR is equipped to damp acceleration vibrations)
PIV	Particle Imaging Velocimetry
PMT	photomultiplier tube
qty	quantity
r_{min}	minimum radial distance from the spherical burner center to the flame edge
r_{max}	maximum radial distance from the spherical burner center to the flame edge
s	second
SAMS	Space Acceleration Measurement System
sccm	standard cubic centimeters per minute, where standard conditions are 0 ºC and 1 atm
SiC	silicon carbide
slpm	standard liters per minute, where standard conditions are 0 ºC and 1 atm
TFP	Thin Filament Pyrometry
UV	ultraviolet
μg	microgravity (9.8×10^{-6} m/s^2)
μm	micrometer (i.e., micron)
ω	frequency

Important Issues

Regarding the Development of these Requirements

1. Inverse flame testing for the Flame Design experiment

In this document, the requirements assume that the inverse flame tests are conducted using the coflow burner where excess unburnt fuel (from the coflow) is actively vented from the chamber. However, the preferred test configuration is with the spherical burner, where the chamber is filled with fuel or a fuel/inert mixture and an oxidizer (or oxidizer/inert mixture) is ejected from the porous sphere. There are safety issues that must be addressed with either approach, but it is has thus far been assumed that it would be difficult to secure approval for testing with the preferred configuration.

2. E-FIELD Flames testing

Ground-based microgravity testing with the test configuration has only just begun, so the existing requirements are based primarily on normal gravity experience. Furthermore, the PI's normal-gravity testing had been focused on gas-jet diffusion flames rather than the coflow configuration to which the SCR panel directed the experiment. Therefore, there is a shortfall in experience with the coflow burner in even normal gravity. While this immaturity is unlikely to significantly effect most hardware requirements, the test matrix and operational requirements are still subject to significant change.

Requirement Development Status

1. Test Matrices

A number of the test matrices in this document are not current and require updating. In the case of the E-FIELD Flames experiment, this is partially because of direction from the SCR review panel to focus on the coflow rather than gas-jet configuration. As a result of this direction, all gas-jet burner testing will be desired for the E-FIELD Flames experiment. It has also been learned by the ACME science team that exploratory testing with cabin air will not be possible because of CIR facility requirement(s). This will necessitate changes in test matrices for both the CLD Flame and Flame Design experiments.

2. Review of Requirements

Through teleconferences with each of the science teams, a detailed review of the requirements has been initiated and is currently underway. Thus far, this review has been limited to experiment configuration and monitoring measurement requirements. The science diagnostic and other requirements have not been updated significantly since the Feb. 2008 SCR.

Outline

Any subsequent text in italics is a comment and not a requirement.

*The word "**shall**" indicates that the specification is a requirement, while the word "**should**" indicates a desired feature.*

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1. Experiment Configuration Requirements

Non-measurement requirements are provided in this section.

1.1. Spherical Burner (Flame Design and s-Flame)

1.1.1. The spherical burner shall be exchangeable during spaceflight for a gas-jet burner, coflow burner, or different spherical burner.[*]

1.1.2. Each spherical burner shall include a porous sphere with a fixed outer diameter. The burner tip diameters shall be 6.4 mm (¼ inch), 9.5 mm (3/8 inch), and 12.7 mm (½ inch) where each is within ±0.3 mm and measured and known within ±0.1 mm. *The burner size is not a variable in either the Flame Design or s-Flame experiments. The general preference is to use the smallest burner that will create a sufficiently spherical flame for the flow conditions. However, smaller burners tend to create flames that are less spherical. In ground-based testing, the Flame Design experiment has regularly used a ¼-inch burner, but the s-Flame experiment has often used a ½-inch burner.*[3,4]

1.1.3. Each spherical burner shall be fed gas via a single supply tube with*:

1.1.3.1. inner diameter that is large enough that the pressure drop in the tube is much smaller than the pressure drop across the burner,[3,*]

1.1.3.2. outer diameter of no more than roughly 10% of the porous sphere diameter,[4,*]

1.1.3.3. length of at least 60 mm from the sphere's center, after which the outer diameter can increase, but the total mass and volume of the burner should be minimized out to a radial position (from the sphere's center) of at least 100 mm.[3,4]

1.1.4. In 2.2 Second Drop Tower testing with **TBD** conditions, each spherical burner shall produce a flame with r_{min}/r_{max} (where r_{min} and r_{max} are relative to the burner center, not flame center) exceeding 0.8, ideally from two orthogonal views, neglecting the region within 20º of burner tube. It is desired that these flames be as spherical as possible and that the ratio exceed a value of 0.95. *It is possible to eliminate particularly bad burners through prescreen testing conducted in a chamber in normal gravity using conditions selected to reduce buoyant effects. For Flame Design, the microgravity acceptance testing would best be conducted under flame "B" conditions (fuel/inert flowing into a pure oxygen atmosphere), where the second choice is flame "C" conditions (pure oxygen flowing into a fuel/inert atmosphere) where the flame is diluted so that it is less sooty.*[3,<4]

1.1.5. The spherical burner shall be positioned such that*:

- 1.1.5.1. supply tube axis is coincident with the CIR chamber axis within ±2 mm (i.e., along its length) and orthogonal to the CIR chamber window axes.[3,*]
- 1.1.5.2. sphere's center is at the intersection of the CIR chamber and window axes within ±2 mm, [3,*]

1.1.6. The ability to vary - between sets of tests - the position of the spherical burner along the chamber axis is desired, but it still must be easy to position the burner at the intersection of the window axes, i.e., as defined in 1.1.5.1. The desired variation does not need to be continuous, but would ideally be in increments of 10 mm, allowing burner (i.e., center of the sphere) positioning at 0, -10, -20, -30, and -40 mm, relative to the intersection of the CIR window axes, i.e., from the plane of the window centers to 40 mm "downward" in the direction of the supply tube.*

1.1.7. The internal (i.e., fluid) volume of the burner from the last solenoid valve to the porous sphere, including the pressure transducer, shall be minimized. *As such, the pressure transducer shall be downstream of the last solenoid valve as described in 2.4.1. It is suggested that the various spherical burners could attach via a quick connect to a single inlet plenum which is equipped with the last solenoid valve and the pressure transducer.*[3,*]

1.1.8. The burners should be fabricated using stainless steel tubing *to match burners used in ground-based testing (e.g., in regard to heat transfer, catalysis, etc.).**

1.1.9. The burner, including the supply tube, shall be capable of withstanding temperatures of at least 0 to 450 ºC. *This temperature limit was based on thermal degradation of the fuel and may restrict options in the sealing of the porous spheres to the burner tubes, e.g., preventing the use of epoxy (as has been used for Flame Design in their ground-based testing). It is anticipated that the burner temperature will be 100 ºC or less in the s-Flame experiment.*[3,4]

1.1.10. See 3.5.1 for the requirements to measure the burner temperature.[3,4]

1.2. **Gas-Jet Burner** (Desired for E-FIELD Flames)

1.2.1. The gas-jet burner (i.e., nozzle) should be exchangeable during spaceflight for a spherical burner, coflow burner, or different gas-jet burner.*

1.2.2. Each gas-jet burner should consist of a straight tube of a constant internal cross-section, where different burners have different diameters and perhaps different cross-sectional shapes. *This could be accomplished by having the tube mounted in a VCO (or similar) blind nut or body that has been drilled through to accommodate the nozzle. It is suggested that the various gas-jet burners could be mounted in the same manner as the spherical burners, i.e., with a quick connect attachment to a common plenum.**

1.2.3. The straight tube (of constant internal cross-section) in a gas-jet burner should be at least 40 times greater in length than the inner diameter (or width) *to create a parabolic velocity profile.**

1.2.4. The plane defined by the nozzle tip should be orthogonal to the burner tube.*

1.2.5. The gas-jet burners should include the following cross-sectional shapes and sizes, where the specified outer diameter applies to at least 10 mm of the burner tip. Greater wall thicknesses (i.e., outer diameters) are allowed further upstream from the tip, although the total volume of the burner should be minimized within about 100 mm of the burner outlet.*

- 1.2.5.1. Circular, 0.4±0.1 mm inner diameter, 0.8±0.1 mm outer diameter *to nominally match nozzles for LSP (STS-107) and SPICE (ISS)**
- 1.2.5.2. Circular, 0.8±0.1 mm inner diameter, 1.2±0.1 mm outer diameter *to nominally match nozzles for LSP (STS-107) and SPICE (ISS)**
- 1.2.5.3. Circular, 1.3±0.1 mm inner diameter, 1.6±0.1 mm outer diameter *to nominally match a nozzle used in ground-based testing*[2]
- 1.2.5.4. Circular, 1.6±0.1 mm inner diameter, 2.0±0.1 mm outer diameter *to nominally match nozzles for SPICE (ISS), LSP (STS-83, STS-94, STS-107), TGDF (STS-87), and ELF (STS-87)**
- 1.2.5.5. Circular, 2.1±0.1 mm inner diameter, 2.4±0.1 mm outer diameter *to match the nozzle (i.e., central tube) in the ACME coflow burner*[2]
- 1.2.5.6. Circular, 2.7±0.1 mm inner diameter, 3.1±0.1 mm outer diameter *to nominally match a nozzle for LSP (STS-83, STS-94)**

1.2.6. Each nozzle's inner diameter and outer diameter (at the tip) should be measured and known to within ±0.05 mm.*

1.2.7. Each nozzle should be internally and externally smooth and the tip shall be free of burs and sharp edges *to prevent turbulence and reduce the likelihood of corona discharges when there is an electric field.*[2]

1.2.8. Each gas-jet burner should be positioned such that*:

- 1.2.8.1. burner axis is coincident with the CIR chamber axis within ±2 mm (i.e., along its length) and orthogonal to the CIR chamber window axes,*
- 1.2.8.2. plane of the CIR chamber window centers is 10±2 mm downstream of the burner outlet.*

1.2.9. The ability to vary - between sets of tests - the position of the burner outlet along the chamber axis is desired, but it still must be easy to position the burner as defined in 1.2.8.2. The desired variation does not need to be continuous, but would ideally be in increments of 10 mm, allowing positioning of the burner outlet at 0, -10, -20, -30, and -40 mm, relative to the intersection of the CIR window axes, i.e., from the plane of the window centers to 40 mm "downward" in the direction of the nozzle.*

1.2.10. Unless otherwise specified, each gas-jet burner should be fabricated from stainless steel tubing *to match nozzles used in ground-based and past space-based testing (e.g., in regard to heat transfer, catalysis, etc.).**

1.2.11. Each gas-jet burner should be capable of withstanding temperatures of at least 0 to 1000 ºC.[*]

1.2.12. See 1.4 for the electrical requirements for the burner.[<2]

1.2.13. See 3.5.1 for the requirements to measure the burner temperature.[2]

1.3. **Coflow Burner** (CLD Flame, E-FIELD Flames, and Flame Design)

1.3.1. The coflow burner shall be exchangeable during spaceflight for a spherical burner, gas-jet burner, or a different coflow burner.[*]

1.3.2. The axisymmetric coflow burner shall consist of a small central tube, i.e., nozzle, (normally for fuel or fuel/inert mixtures) within a larger outer coflow "tube" where the coflow gas (e.g., air) flows through the annulus between the tubes. The outer coflow "tube" does not need to have a constant cross-section but can be smoothly converging (toward the outlet). *The use of a smoothly converging nozzle, with no steps or other rapid changes, will minimize the boundary layer on the nozzle's inner wall, which is desired as specified in 1.3.10.**

1.3.3. The central and coflow tubes shall be concentric within ±0.3 mm along their common length.[1,*]

1.3.4. The planes defined by each tube outlet shall be orthogonal to the burner axis. The outlet surface across the annulus (e.g., honeycomb, mesh) shall be orthogonal to the burner axis and flat to within ±0.1 mm.

1.3.5. The outlet (tip) of the nozzle (i.e., central tube) shall be 0.5 to 1.0 mm downstream of the annular outlet surface, where that distance shall be known to within ±0.2 mm. The outlet of the outer tube should be 0.0 to 0.5 mm downstream of the annular outlet surface.[1,2,*]

1.3.6. The circular nozzle (i.e., central tube) shall have a 2.1±0.1 mm inside diameter and a 2.4±0.1 mm outer diameter *where the thin wall helps minimize the "dead space" (where gas is not exiting) in the radial flow profile at the burner outlet*. The nozzle's inner diameter shall be constant for a length of at least 40 times the inner diameter *to create a parabolic velocity profile*. At **TBD** (10 mm?) or more upstream of the burner outlet, the wall thickness can increase from the specified value, *e.g., to stiffen the tube*. The nozzle's inner diameter and outer diameter (at the tip) shall be measured and known to within ±0.05 mm.[<1,*]

1.3.7. The nozzle shall be internally and externally smooth and the tip shall be free of burs and sharp edges *to prevent turbulence and reduce the likelihood of corona discharges when there is an electric field.*[2,*] 1.3.8. The internal (i.e., fluid) volume extending from the gas flow control up to and including the nozzle (i.e., central tube) shall be minimized. *A larger volume between the mass flow controllers and burner outlet increases the time necessary to change between different experimental flow conditions. Minimizing that volume will help to minimize the changeover time between two flow conditions.*[1]

1.3.9. At the burner outlet, the (outer) coflow tube shall have an inner diameter of 25±0.5 mm. At the burner outlet, the coflow tube's inner diameter shall be measured and known to within ±0.1 mm.[1]

1.3.10. The burner shall have a uniform flow profile especially (at radial positions) near the outlet of the nozzle. The burner gas shall be ejected parallel to the chamber axis and without either swirl or turbulence. The boundary layer outside the nozzle (i.e., central tube) and inside the (outer) coflow tube shall be minimized. The coflow should ideally have a plug flow velocity profile (i.e., an exit velocity that is independent of the radial position) for velocities up to 50 cm/s. *This can be accomplished with velocities up to 35 cm/s with a minimum of two seamless Haynes 214 honeycomb disks of cell size 1/64 in. that are at least 1/4 in. thick. The first honeycomb disk could be placed above the coflow entrance and the second honeycomb disk at the burner exit. Special care should be taken to ensure that penetration of the central tube through honeycomb is symmetric. This might be accomplished through careful cutting of the honeycomb, either with a tight fit around the central tube or with a symmetric gap comparable in size to the cell size of the honeycomb. The lifted flames, as planned for these experiments, are very sensitive to minor inconsistencies that can result (for example) in cutting the honeycomb. While honeycomb (of sufficient thickness as compared to the cell size) prevents swirl, other material such as layer(s) of mesh can be used to reduce the boundary layer.*[<1,*]

1.3.11. The burner's flow profile, across a plane orthogonal to the burner axis and within at least 0.5 mm of the nozzle outlet, shall be well-documented, especially near the outlet of the nozzle. The spatial uniformity shall be verified by 1g measurement of the velocity field using a cold flow (i.e., with no flame) through both the annulus and the nozzle. The flow profile will be measured for a range of flow velocities from 10 to 50 cm/s for at least matched velocities, and ideally also for unmatched velocities. *Smoke wire imaging is a suggested way to characterize the burner flow, where it is important to rotate the wire relative to the burner to ensure the axisymmetry of the flow for at least one flow condition.*[1,*]

1.3.12. It is highly desired that the coflow flame be axisymmetric over the full range of flow conditions. This is especially important for lifted flames, where the flame is detached and downstream from the nozzle tip, where the plane of the flame's base should be orthogonal to the burner axis. The axisymmetry of the flame should be demonstrated over the full range of flow conditions in 1g (for at least matched velocities from 10 to 50 cm/s) and for a limited set of conditions in 0g.[2]

1.3.13. It is desired that any flow control media used in the coflow burner, for either the nozzle or annular flow, allow the passage of particles of at least **TBD** (5 microns?) *to enable 1g characterization of the burner flow using techniques such* *as Particle Imaging Velocimetry (PIV) that require flow seeding.* It is also desired that the burner be capable of disassembly and reassembly *to allow for cleaning of seed particles from the burner.*[1,*]

1.3.14. The coflow burner shall be positioned such that*:

1.3.14.1. burner axis is coincident with the CIR chamber axis within ±2 mm and orthogonal to the CIR chamber window axes,*

1.3.14.2. plane of the CIR chamber window centers is 10±2 mm downstream of the burner outlet.[1,]*

1.3.15. The ability to vary – between sets of tests - the position of the burner outlet along the chamber axis is desired, but it still must be easy to position the burner as defined in 1.3.14.2. The desired variation does not need to be continuous, but would ideally be in increments of 10 mm, allowing positioning of the burner outlet at 0, -10, -20, -30, and -40 mm, relative to the intersection of the CIR window axes (i.e., from the window axes to 40 mm "downward").*

1.3.16. The nozzle should be fabricated from stainless steel tubing *to match nozzles used in ground-based and past space-based testing (e.g., in regard to heat transfer, catalysis, etc.).**

1.3.17. The burner shall be capable of withstanding temperatures of 0-1000 ºC, *though only minimal heat transfer to the burner is expected in most CLD Flame testing. Nonetheless, elevated temperatures are possible at ignition or extinction, and during the E-FIELD Flames or Flame Design experiments (especially in tests with elevated oxygen concentrations).*[<1,3]

1.3.18. See 1.4 for the electrical requirements for the burner.[2]

1.3.19. See 3.5.1 for the requirements to measure the burner temperature.[2]

1.4. Burner as Electrode (E-FIELD Flames)

1.4.1. Each burner, with the exception of the spherical burners, shall have a resistance of less than 1 Ohm (e.g., along its length). For the coflow burner, the nozzle (i.e., central tube) shall be at the same potential as the annular outlet surface (e.g., mesh, honeycomb). *The burner must be electrically conductive so that it is not an obstruction to the ion current, but rather a pathway.*[2]

1.4.2. Neglecting wiring associated with the burner temperature measurement, the burner shall be electrically insulated from any mechanism that supports it within the chamber. An exception is the spherical burners which do not need to meet this requirement. All of the electrical insulators shall withstand 20 kV DC without breaking down and shall have a combined resistance of no less than 1 giga-ohm.[2]

1.5. Electrode Mesh (E-FIELD Flames)

1.5.1. The flat, circular electrode mesh shall be composed of copper mesh with 16 to 22 wires per 25.4 mm (1 inch) with a wire diameter of 0.38 to 0.64 millimeters (0.015 to 0.025 inches).[2]

1.5.2. The edge of the mesh electrode should be electrically attached (e.g., soldered) to a copper ring with a 2 to 3 mm cross sectional diameter. To the extent possible, the edge should be smooth and free of burs and sharp edges, *to reduce the likelihood of electrical discharge (e.g., arcing). This might be best accomplished by machining a groove into the copper ring in which the mesh can be set for soldering. Otherwise, any prongs on the edge of the mesh should smoothed off*.[2]

1.5.3. The ring forming the edge of the electrode mesh shall have an outer diameter of at least 100±1 mm. It should be as large as possible, but where the axial distance from the burner tip to the electrode mesh (up to 100 mm, but 50 mm by default per 1.5.5) is shorter than the distance between the electrode mesh and any other conductive surface. The outer diameter of the ring shall be known to ±1 mm.[2]

1.5.4. The electrode mesh shall be positioned so that its center is on the CIR chamber axis (and thus the burner axis) within ±2 mm and its plane is orthogonal to the CIR chamber axis within ±2 mm.*

1.5.5. The electrode mesh shall be 50±1 mm downstream of the gas-jet and coflow burner nozzle outlet. It is desired that it be possible to place the electrode mesh at a range of axial positions (whether fixed or in continuum) from 20 to 100 mm downstream of the burner outlet.[2]

1.5.6. At 10 kV, the current measured without a flame between the electrode mesh and the burner should be less than 50 nanoamps. *It is suggested that this can be accomplished by insulating the electrode mesh from any mechanism that supports it within the chamber, where the combined resistance of the insulation is no less than 200 giga-ohms. The electrical insulators should be capable of withstanding 20 kV without breaking down. The indicated voltage is twice that of the electric field (specified in 1.6), providing a safety factor of 2.* [2]

1.6. **Electric Field** (E-FIELD Flames)

1.6.1. The electric field generator shall be capable of DC and ideally AC operation and meet the following requirements[2]:

1.6.1.1. DC Field (required)[2]

1.6.1.1.1. Voltage range: ±10 kV [2]

1.6.1.1.2. Voltage accuracy: ±0.1% of the set point[2]

1.6.1.2. AC Field (desired)[2]

1.6.1.2.1. Voltage range: 0-10 kV_p [2]

1.6.1.2.2. Voltage accuracy: ±0.1% of the set point[2]

1.6.1.2.3. Frequency range: 0-1000 Hz, where a set of fixed frequencies (e.g., 10, 20, 30, …, 100, 200, 300, … Hz) are acceptable, but continuous frequency adjustment is preferred[2]

1.6.2. The capability to vary the voltage potential, in both sign and magnitude, to uplinked values is required. If an AC electric field is provided as desired, then the capability to vary the field type (DC or AC) and frequency (for an AC field) and set each to uplinked values is also required.[2]

1.6.3. Without exception, nothing electrically conductive shall come into contact with the burner or electrode mesh when the electric field is active.[2]

1.6.4. Without exception, a cylindrical zone between the burner and the electrode mesh shall be kept free of any electrically conducting objects during operation of the electric field. The zone's diameter shall be at least 30 mm greater than the electrode mesh diameter, and the zone will extend axially from the burner outlet to at least 20 mm downstream of the electrode mesh.[2]

1.7. Gas Supply

The identified gases below assume the capability to produce diluted fuels on orbit, by mixing the source fuel and an inert. It is further assumed that the oxygen compatibility of the ACME insert will not limit the maximum oxygen concentration in the ACME oxidizer bottles. If these assumptions are inappropriate, then different source gases will be required to accomplish the experiment objectives.

1.7.1. The following source gas compositions are **required**, where mixtures are given on a volume (molar) basis*:

1.7.1.1.	fuels (6)	H_2, CH_4, C_2H_4, 44.4/55.6 H_2/CH_4, 55.6/44.4 H_2/CH_4, 66.7/33.3 H_2/CH_4*
1.7.1.2.	oxidizers (5)	85/15 O_2/N_2, 50/50 O_2/N_2, 30/70 O_2/N_2, 21/79 O_2/N_2, 85/15 O_2/He*
1.7.1.3.	inerts (2)	N_2, He*

1.7.2. The following source gas compositions are **highly desired**, where mixtures are given on a volume (molar) basis*[3,4]:

1.7.2.1.	fuels (0)	none*
1.7.2.2.	oxidizers (1)	85/15 O_2/CO_2*[3,4]
1.7.2.3.	inerts (1)	CO_2*[3,4]

1.7.3. The capability to use partially premixed source gases consisting of a mixture of fuel(s), oxygen, and perhaps inert(s) is desired *to enable future studies of partially premixed flames*.

1.8. Burner Gas Delivery

It is suggested that the gas delivery be controlled with an exchangeable set of mass flow controllers, where a good candidate may be the Hastings HFC-D-302 because of its auto-zero function, high accuracy, and reasonable response time.

1.8.1. When in use, the gas-jet burner and spherical burner shall be supplied with either a fuel source gas or a mixture of a fuel source gas and an inert source gas. The capability to supply these burners with a mixture of (1) a fuel source gas, (2) an oxidizer source gas, and (3) an inert source gas is highly desired *to enable future studies of partially premixed flames*.*

1.8.2. In normal use, the coflow burner's nozzle (i.e., central tube) shall be supplied with either a fuel source gas or a mixture of a fuel source gas and inert source gas. The capability to supply the nozzle with a mixture of (1) a fuel source gas, (2) an oxidizer source gas, and (3) an inert source gas is desired *to enable future studies of partially premixed flames*. In normal use, the coflow annulus shall be supplied with an oxidizer source gas or a mixture of an oxidizer source gas and an inert source gas.[>1,*] 1.8.3. The coflow burner shall also be capable of inverse operation, where the nozzle (i.e., central tube) is supplied with an oxidizer source gas or a mixture of an oxidizer source gas and an inert source gases. The capability to supply the nozzle with a mixture of (1) a fuel source gas, (2) an oxidizer source gas, and (3) an inert source gas is desired *to enable future studies of partially premixed flames*. For inverse operation, the coflow annulus shall be supplied with either a fuel source gas or a mixture of a fuel source gas and an inert source gas.[3,*]

1.8.4. The capability to mix (as described in 1.8.1 to 1.8.3) the source gases (described in 1.7) and vary the composition of the burner gases to uplinked set values is required. The composition of any mixture should be controlled within ±0.005 mole fraction, preferably within 1 s. The mixture composition (i.e., gas concentrations) ejected from the burner shall be known as a function of time*, for example, through knowledge of the system response time.* The gases shall be well mixed, *e.g., by providing for an adequate mixing length (or time)*.[3]

1.8.5. The capability to vary all gas flow rates and set them to uplinked set values is required. It is required that they be controlled within ±5% of the set point, and desired that they be controlled within ±1% of the set point, preferably within 1 s, including flow start and stop. Shutoff capability is required for all gases. *Flames are highly dependent on the burner flow and most mass flow controllers have an uncertainty based on the full flow, where a typical value is 1% of the full scale flow. Like many instruments, the accuracy is poor at very low values compared to full scale. This requirement effectively limits the useful range of a typical flow controller (with 1% full scale uncertainty) from 20% to 100% of the flow. To meet the desired accuracy, a typical flow controller should only be used for flows of 80% to 100% of the full scale flow. Given the wide range of required flows (as specified in the test matrices) and the upmass and operational constraints, the design of the flow control is especially important for this experiment.*[<3]

1.8.6. For the **spherical burner**, the flow system shall provide source fuel flow of 0 to 0.5 slpm (on a N2 basis) and source inert gas flow of 0 to 4 slpm (on a N2 basis). *For the s-Flame experiment, an inert gas flow of up to 2 slpm (on a N2 basis) should be adequate.*[3,4]

1.8.7. For the **gas-jet burner**, the flow system shall provide 0 to 0.1 slpm (on a N2 basis) of the source fuel plus 0 to 0.1slpm (on a N2 basis) of the source inert. The capability for greater nozzle flows is desired for possible future ACME experiments.[2,*]

1.8.8. For **normal operation of the coflow burner**, the flow system shall provide 0 to 0.2 slpm (on a N2 basis) of the source fuel plus 0 to 2 slpm (on a N2 basis) of the source inert to the nozzle (i.e., central tube). The flow system shall provide for a burner coflow of 0 to 15 slpm of oxidizer to the coflow annulus.[1,2]

1.8.9. For **inverse operation of the coflow burner**, the flow system shall provide 0 to 2 slpm of the source fuel plus 0 to 20 slpm of the source inert to the coflow annulus. The flow system shall provide for a burner coflow of 0 to 2 slpm to the central tube.[3]

1.8.10. The flow system shall be capable of providing gases at the maximum flow rates for at least 25 s.[4]

1.8.11. Neglecting flame heating, the burner gas shall be delivered at 300K±10 K.[4]

1.8.12. The burner gas should be dry and the net amount of trace contaminants should be less than a mole fraction of 0.0001.[3]

1.9. Ignition

While hot-wire igniters have been effectively used in many combustion experiments, special care is required for ACME because of the testing with elevated oxygen (for the Flame Design experiment) which leads to higher flame temperatures which in turn could significantly shorten igniter life. Hot Surface Ignition (HSI), which is often used in furnaces, may be better for ACME than hot-wire ignition.

1.9.1. The igniter should reliably ignite all initial flow conditions. Reliable ignition should be verified in 1g at the limiting (i.e., extreme) conditions in the test matrices for each burner. *For the spherical burner, it is suggested that the ignition occur at about 3 mm from the porous sphere. For the gas-jet and coflow burners, the ignition should occur within the mixing layer between the nozzle and coflow (and not centered on the burner axis).*[3,4,*]

1.9.2. For the spherical burner, ignition should occur as quickly as possible, and preferably within 0.5 s, after the start of gas flow from the burner. The occurrence of some failed ignitions is an acceptable trade to achieve rapid ignition. It is desired that quick and reliable ignition be verified in ground-based microgravity testing for at least the spherical burner. *Rapid ignition is not required for the gas-jet and coflow burner tests.*[3,4,*]

1.9.3. Hydrodynamic disturbance from igniter retraction shall be minimized by inserting the igniter at least 30 s prior to ignition, and removing it from the free area within 0.5 s after ignition detection. *The disturbance can be minimized through a linear rather than a sweeping retraction, and by limiting the speed of the retraction (as a rapid retraction could disturb the flame).*

1.9.4. The igniter energy output shall be minimized *to ensure minimal effects on subsequent flame behavior and avoid igniter burnout. As one example of implementation, the igniter should not be energized longer than required.*[3,*]

1.9.5. The capability to vary the ignition duration and set it to an uplinked value is required.*

1.10. Ambient Environment

1.10.1. The capability to vary the gas composition within the chamber and set it to an uplinked composition is required *(where the uplinked composition could be a set of partial pressures)*. Prior to each test, the chamber shall contain the specified gas composition, consisting of an oxidizer, inert, or mixture of oxidizer and an inert gas within ±0.01 mole fraction of each concentration. The chamber gas should be dry and the net amount of trace contaminants, including H2O and CO2, should be less than a mole fraction of 0.01. *Ambient gas may be scrubbed and restored to these standards between tests, rather than discarded and replaced.*[<3,<4]

1.10.2. Prior to each test, the chamber atmosphere shall be well mixed. *This can be accomplished with the CIR chamber fan.**

1.10.3. Quiescent conditions shall be achieved with a hold period after filling, venting or actuator motion, and prior to ignition. The duration of the hold period shall be at least 300 s and uplinkable *(where the uplink could be to initiate the test rather than the hold duration itself)*. During testing, convective disturbances shall be limited to those caused by burner gas flow, combustion, the igniter, and the motion of the mesh electrode and any diagnostics (e.g., the TFP array).[<3]

1.10.4. The capability to vary the initial chamber pressure in the range 0.1 to 3 atm absolute and set it within ±3% of an uplinked value is required.[<3,<4]

1.10.5. The initial ambient temperature shall be 290 to 310 K and uniform within ±5 K, *and can be ensured by minimizing heat sources.*[<3,<4]

1.10.6. The chamber free volume shall be maximized, with 80 liters required, and should generally be as symmetric as is feasible relative to the chamber axis and the intersection of the CIR chamber window axes. *A large free volume will help ensure constant far field conditions (e.g., temperature, pressure, composition) throughout the duration of each test. The free volume can be made symmetric by distributing components uniformly at similar distances from the burner outlet.* [3,<4]

1.10.7. The capability to actively vent the chamber is required for at least some coflow burner tests, where the chamber pressure shall be kept constant within ±0.02 atm throughout the duration the test. The chamber pressure shall not be controlled by varying the burner gas flow because that is prescribed for each test (i.e., in the test matrix). The choice between constant pressure (i.e., active venting) or constant volume (i.e., sealed chamber) will be specified via uplink. The exhaust plenum for this venting shall be axisymmetric relative to the chamber, and should be at least 300 mm from the intersection of the CIR window axes. *Close or asymmetric venting could disturb the flame.* Ideally, the exhaust plenum should be as far downstream of (i.e., above) the coflow burner as practical.[1,*]

1.10.8. For the spherical burner tests, a free area at least 200 mm in diameter centered on the spherical burner (or the intersection of the CIR chamber window axes) shall be kept clear of solid objects except the burner and tube. It is desired that the free area be as large as possible. The temporary insertion of the igniter and the presence of any probes (including TFP fibers) are allowed exceptions. *The purpose of this free zone is to ensure the symmetry of the velocity, thermal and composition fields.*[4]

1.10.9. For the gas-jet burner and coflow burner tests, a cylindrical free area that is at least 200 mm in diameter extending downstream from the burner outlet at least 100 mm shall be kept clear of the solid objects. It is desired that the free area be as large as possible. The temporary insertion of the igniter and the presence of any probes (including TFP fibers) are allowed exceptions. The electrode mesh is also an allowed exception for tests utilizing the electric field. *The purpose of this free zone is to ensure the symmetry of the velocity, thermal and composition* *fields. It is distinct from the free zone for the electric field which is specified in 1.6.4.*[1,2]

1.10.10. Ambient disturbances shall be limited to those caused by burner flow, combustion, the igniter, the motion of any probes, and g-jitter. See the acceleration requirements in 1.10.11.[3]

1.10.11. Quasi-steady acceleration level should be less than 5 μg on each axis. Impulses (integral of acceleration over time) should be less than 25 μg-s on a time scale of less than 5 s. The amplitude of any vibrations should be less than $A = 4.5 \times 10^{-5}\ \omega g$ where A is the amplitude, ω is the frequency of vibration and g is 9.8 m/s^2. *It is expected that this requirement will be met by the environment on the ISS and specifically the CIR which is equipped with an Passive Rack Isolation System (PaRIS).*[3,4]

1.10.12. To the extent possible, there should be nothing other than the flame that emits within each optical detector's field of view and spectral range of sensitivity. Ideally, all imaging and radiant emission measurements (e.g., made by cameras, thermopile detectors, photomultiplier tubes, etc.) should have a non-reflective background within their spectral range of sensitivity. Ideally, the emissivity of all hardware within a detector's field of view should be known and greater than 0.9 across the detector's spectral range of sensitivity. Allowed exceptions include the probe tips, TFP fibers, burner outlet, and the temporary insertion of the igniter. *Based on testing with samples, the CIR chamber interior should have minimum emissivities of 0.9286 and 0.5628 for wavelength ranges of 0.25-0.7 and 0.7-20 microns, respectively (per verification CIR-VER-3960 and procedures CIR-TPP-3953).*[4,*]

1.11. Data Synchronization and Recording

1.11.1. All collected data and images shall include the collection time using a common reference time, where each measurement should be synchronized within its temporal resolution.[<2,3]

1.11.2. Unless otherwise noted, all non-imaging measurements shall begin at an uplinked time that is up to 5 minutes prior to ignition and continue to an uplinked time up to 5 minutes after extinction detection. *Pre-ignition and post-extinction durations of 30 seconds each is adequate for the s-Flame experiment.*[3,4]

1.11.3. Unless otherwise noted, all imaging measurements shall begin at an uplinked time that is up to 5 minutes prior to ignition and continue to an uplinked time up to 5 minutes after extinction detection. *Post-extinction imaging is important to verify that the flame truly extinguished and didn't merely seem to do so based on the extinction detection. The start and stop times for imaging may not match those times for non-imaging measurements because of the much greater memory and thus downlinking time. In this regard, note that it is envisioned that only a fraction of the recorded imaging data may be downlinked for each test. The fraction could be selected after a review of non-imaging data, or perhaps after the review of the image data from a single camera. In the latter case, the downlink times might not be consistent for all cameras.*[3,4,*]

2. Monitoring Measurements Requirements

This section describes needed measurements of the initial, boundary, and similar experiment conditions, e.g., to enable modeling of the experiment and analysis of the results.

2.1. Chamber Pressure

It is expected that this measurement will be satisfied by the pressure transducer(s) with which the CIR chamber is already equipped.

2.1.1. The absolute chamber pressure shall be measured with an accuracy of ±1% of reading. [3,4]

2.1.2. The pressure measurement range shall be 0.1 to 4 atm absolute.[<3.,<4]

2.1.3. The chamber pressure shall be measured at 1 sample/s or faster with a temporal resolution of 0.5 s or less.[3,<4]

2.2. Chamber Oxygen Concentration (for tests without active venting)

This requirement could potentially be met by CIR's gas chromatograph if it were launched, but it is more likely that it will be met with detector(s) on the ACME insert. The use of Electrovac D12-60-250 zirconia sensor, which is extremely dependent on the pressure, but less sensitive to other gases than typical oxygen sensors, was under consideration for the FEANICS insert (which is now defunct).

2.2.1. At a minimum, the oxygen concentration of the well-mixed chamber atmosphere shall be measured before and after each test (without active venting) with an accuracy of ±0.01 mole fraction.[*,3,4]

2.2.2. It is desired that the oxygen concentration be measured during testing (without active venting) as a function of position and time. Measurements should be made on unobstructed paths to the spherical burner (or intersection of the CIR chamber window axes) at radii of 10 cm and 20 cm (or near the chamber wall). It is desired that the oxygen concentration be measured at 1 sample/s or faster with a temporal resolution of 0.5 s or less.[3,<4]

2.2.3. The oxygen concentration measurement range shall be from a mole (volume) fraction of 0.05 to 0.05 greater than the maximum concentration possible. For example, if the maximum oxygen concentration is 0.5, then the measurement range should be 0.05 to 0.55 mole fraction.[3]

2.3. Gas Flowrates

As suggested in 1.8, the measurement could be made using an exchangeable set of mass flow controllers, where a good candidate may be the Hastings HFC-D-302 because of its auto-zero function, high accuracy, and fast response time.

2.3.1. It is required that each gas flowrate shall be measured with an accuracy of ±5% of the reading or better. It is desired that each gas flowrate be measured within ±1% of the reading. *As an example, if a flow meter has a full scale uncertainty of ±1%,* *then its use should be limited to flows that are no less than 20% of its maximum. Compare with requirement 1.8.5 for flow control. The suggested Hastings HFC-D-302 has an uncertainty of only ±(0.2% full scale + 0.5% of the reading).*[3,4]

2.3.2. The gas flowrate ranges are specified in 1.8.*

2.3.3. Each measurement shall be made at 10 samples/s or faster, preferably with a temporal resolution of 0.1 s or less. *While some commercial mass flow controllers and meters have response times of a second or more, others commercial units (e.g., manufactured by Hastings and Sierra) have response times that are on the order of 100 ms. However, the suggested Hastings HFC-D-302 has a settling time of 0.5 s.* [<3]

2.4. Burner Pressure Differential (for spherical burner tests)

It is suggested that the spherical burners could attach to the ACME insert via a quick connect to a common inlet plenum equipped with a differential pressure transducer. Although such measurements are not important for tests with the gas-jet burners, it is suggested that they could connect in the same way to the plenum.

2.4.1. The pressure differential across the spherical burner (i.e., between the supply tube inlet and the chamber) shall be measured with a required accuracy of at least ±2% of the reading, and a desired accuracy of ±1% of the reading. The pressure differential shall be measured downstream of any valves so that it indicates the burner's pressure regardless of valve activation.[3,4,*]

2.4.2. The measurement range shall be from 0.1 to roughly 1.5 times the pressure drop across the spherical burners at a flow rate of 5 slpm (on a N2 basis) in cold flow testing (i.e., with no flame). *The pressure drop and thus flow measurement range will depend on the spherical burner design and fabrication.*[3,4,*]

2.4.3. The measurements shall be made at a frequency of 10 samples/s or faster, preferably with a temporal resolution of 0.1 s or less.[3,4,*]

2.5. Burner Gas Temperature (Desired)

It is suggested that the gas temperature could be measured with a thermocouple within a common inlet plenum used for all of the spherical and gas-jet burners. The coflow burner could be similarly equipped with thermocouples.

2.5.1. The temperature of each burner gas stream after mixing should be measured with an accuracy of ±1 ºC.[3]

2.5.2. The measurement range should be 15-30 ºC.[3]

2.5.3. Each measurement should be made at the entrance plenum to the burner.[3]

2.5.4. The measurements should be made at 1 sample/s or faster with a temporal resolution of 0.5 s or less.[3,<4]

2.6. Electric Potential (E-FIELD Flames)

It is suggested that this measurement could be enabled with use of a calibrated voltage divider.

2.6.1. The electric potential between the mesh electrode and the high voltage (HV) ground terminal shall be measured to within ±1% of the reading.[2]

2.6.2. The measurement range shall be ±10 kV.[2]

2.6.3. Measurements shall be taken at the same sampling rate as the ion current measurements; see 3.9.[2]

2.7. Acceleration

It is expected that these requirements will be met with the SAMS and MAMS instruments that are already in the laboratory module in the ISS.

2.7.1. The chamber acceleration shall be measured on each orthogonal axis with a precision of $\pm 10^{-5}$ g and an accuracy of $\pm 3 \times 10^{-5}$ g. It is desired that the accuracy be ±5% of the reading.[3,4]

2.7.2. The measurement range shall be 10^{-5} to 10^{-2} g.[3]

2.7.3. The measurements shall be made at 60 samples/s or faster with a temporal resolution of 1/120 s or less.[3]

3. Science Diagnostics Requirements

This section describes imaging and other measurements of the flame and flame effects. The corresponding Science Data End Products (SDEPs) are listed for the four ACME experiments.

3.1. Color Imaging

SDEPs: 1A1,4-6; 1B1,4-7; 2A2,5,8; 2C2,4; 2D2,4; 3A1,3-4; 3B1,3,5-7; 3C1,3-5; 4A1-2,4; 4B1-2,4; 4C2,4-5

It is expected that the color imaging requirements will be met with a new CIR camera developed by and for ACME.

3.1.1. The color imaging shall have a wavelength response of 0.4 to 0.7 μm nominally matching human vision.[3,4]

3.1.2. It is highly desired that the camera be as sensitive to the light at 431 nm as the typical human eye. *While other methods are acceptable, it is suggested that this can be verified in 1g testing with a stable light source, a 431-nm bandpass filter, and a set of neutral density filters (if the luminosity of the light source cannot be controlled directly). If the camera cannot see dim blue light that is visible to the human eye, then it doesn't meet this specification.**

3.1.3. While set to be as sensitive to 431-nm light as a human eye (see 3.1.2), it is desired that the imaging not saturate in the luminous soot-containing regions of the flame. In other words, it is desired that the imaging have as large a dynamic range as practical, as can result from a large camera bit depth. It is required that the imaging have a bit depth of at least 3x8 bit depth.[<1,<3,*]

3.1.4. The camera shall have a resolution of 0.15 mm or better at the focal plane, where a resolution of 0.05 mm or better is desired.[<1,<3]

3.1.5. The camera shall have a **TBD** depth of field.*

3.1.6. The camera shall have an adjustable gain (or iris) to accommodate varying flame intensities.[4]

3.1.7. For the **spherical flames**, the camera shall view the entire area within about 45 mm of the burner center (i.e., about 90 mm in diameter), where a 120-mm diameter is preferred. The camera should preferably allow zooming via uplink prior to ignition to within 30 mm of the burner center.[3,4]

3.1.8. For the **gas-jet and coflow flames**, the camera shall view the area within 10 mm of the burner axis (i.e., 20-mm width centered on the burner axis), where a 25-mm width is preferred. The FOV shall extend from the burner outlet to at least 50 mm downstream of (i.e., above) the central fuel tube, where a length of up to 120 mm may be preferred for some tests.[1,2]

3.1.9. One view is required and a second orthogonal view is desired.[3,4]

3.1.10. The measurements shall occur at 30±**TBD** fps or faster with a temporal resolution of 1/30 s or less. Recording at 60 fps or faster is preferred *for most experiments. Imaging at lower framing rates, such as 10 frames/s, is acceptable for the CLD Flame experiment.*[>3,>4]

3.1.11. A lamp shall be available for optionally illuminating the view of the color camera before or during tests. Lamp control shall be accomplished via uplink prior to ignition.[3]

3.2. Ultraviolet (UV) Imaging

SDEPs: 1A2-6; 1B2-5; 2A2,5,8; 2D2,4; 3A3; 3B3,6-7; 3C3-5; 4A1-2; 4B1-3; 4C2,4

It is expected that the requirements for UV imaging will be met with the CIR's LLL-UV camera which is already equipped with an OH filter.*

3.2.1. These imaging requirements are generally similar to the color imaging requirements (3.1) except that the camera and all associated optics are optimized for UV imaging through an OH* filter (310 nm) with a 10 nm FWHM, i.e., Full Width at Half Maximum transmission.[3,4]

3.2.2. Alternate imaging through a CH* filter (431 nm) with a 10 nm FWHM is desired, as is imaging with no interference filter where the camera and optics should be optimized for a range of at least 280 to 700 nm. *Although the E-FIELD Flames experiment normally images CH* emission in their 1g studies, current results indicate that it is collocated with the OH* emission making that default measurement acceptable.*[3,4,*]

3.3. Infrared (IR) Imaging (Desired)

SDEPs: 2A9; 4A3; 4B1-2; 4C2

It is unfortunately expected that there will be no IR imaging for ACME. Although the LLL-IR camera was developed for CIR, its spectral range is very limited and does not include emission from the CO_2 and H_2O produced by combustion.

3.3.1. These imaging specifications are generally similar to the color imaging requirements (3.1) except that the camera and all associated optics are optimized for IR for a range of 1 to 5 µm. *That spectral range is important because it includes emission from the* CO_2 *and* H_2O *produced by combustion.*[4]

3.3.2. Optional imaging through **TBD** interference filter(s) is desired*, for example to image spectral emissions from* CO_2 *(4.31 µm) or* H_2O *(1.87 µm).**

3.4. Refractive Index Imaging (Desired)

SDEPs: 2A9; 4A3

It is expected that there will be no refractive index imaging unless it can be accomplished with the existing illumination package without an additional camera (i.e., beyond the HiBMS, LLL-UV, and ACME developed color camera).

3.4.1. Imaging of the second derivative of refractive index is desired, but imaging of the first derivative is preferred. *This could be accomplished through shadowgraph or schlieren photography, respectively, which reveal changes in refractive index (which within flames primarily result from changes in density). Other imaging or measurement methods are acceptable.*[2,<4]

3.4.2. Other specifications are similar to color imaging requirements (3.1).*

3.5. Temperature

3.5.1. Burner

3.5.1.1. The **spherical burner** surface temperature shall be measured at a location outside of the region within 20° of the burner tube.[3,4]

3.5.1.2. The **gas-jet burner** surface temperature shall be measured on the exterior at **TBD**±**TBD** (down) from the outlet (tip).[2]

3.5.1.3. The coflow burner surface temperature shall be measured on the exterior surface of the central tube at **TBD**±**TBD** (down) from the outlet (tip).[1,2]

3.5.1.4. If the measurement involves a probe, the probe shall be smaller than 130 microns.[3]

3.5.1.5. The measurements shall have a precision of ±2 °C and an accuracy of ± 5 °C.[3,>4]

3.5.1.6. The measurement range shall be **TBD**.*

3.5.1.7. The measurements shall be made at 1 Hz or greater with a temporal resolution of 0.5 s. Measurement at a frequency of 10 Hz or higher is preferred.[3,<4,*]

3.5.2. Hot Soot-Containing Regions

SDEPs: 1A7-8; 1B8-10; 3A2-3; 3B2-3,5,7; 3C2-3,5; 4A3-4; 4B1-4; 4C2,4-5

3.5.2.1. Temperatures shall be measured in the hot soot-containing region. *It is suggested that these temperatures will be measured with multi-line emission using the HiBMS camera followed by deconvolution. Other methods that meet the requirements also are acceptable.*[3]

3.5.2.2. For the **spherical flames**, the minimum measurement region shall be the region within 60 mm of the burner center (i.e., 120 mm diameter).[3,4]

3.5.2.3. For the **gas-jet and coflow flames**, the measurement region shall be the area within 10 mm of the burner axis (i.e., 20 mm diameter), centered on the burner axis, extending from the burner outlet to 25±1 mm downstream of (i.e., above) the central tube.[1]

3.5.2.4. Measurements should be possible for regions with soot temperatures in the range of 1200-2100 K and soot volume fractions in the range of 0.1-20 ppm. NASA will provide the calibration data, but the investigators are responsible for the verification analysis.[<1,<3]

3.5.2.5. The measurements should have a precision of ±25 °C and an accuracy of ±50 °C. NASA will provide the calibration data, but the investigators are responsible for the verification analysis.[3]

3.5.2.6. Within the measurement region and the constraints in 3.4.2.4-5, the temperature shall be measured every 0.15 mm, but 0.1 mm or less is preferred.[<3]

3.5.2.7. The sensor shall allow variable gain via uplink prior to ignition.[3]

3.5.2.8. The measurements shall occur at least every 5 s with a temporal resolution of 5 s.[3]

3.5.2.9. The measurements shall start and stop according to uplink prior to ignition. *Not all the data will be saved.*[3]

3.5.3. <u>Hot Soot-Free Regions</u>

SDEPs: 1A7-8; 1B8; 3A2-3; 3B2-3,5,7; 3C2-3,5; 4A3-4; 4B1-4; 4C2,4-5

3.5.3.1. Temperature distributions orthogonal to the chamber axis shall be measured in the hot soot-free region. *It is suggested that these temperatures be measured using multi-line Thin Filament Pyrometry (TFP) using the HiBMS camera. Other methods that meet the requirements also are acceptable.*[3]

3.5.3.2. For the **spherical flames**, the minimum measurement region shall be the region within 60 mm of the burner center (i.e., 120 mm diameter).[4]

3.5.3.3. For the **coflow flames**, the measurement region shall be the area within 10 mm of the burner axis (i.e., 20 mm diameter), centered on the burner axis, extending from the burner outlet to 25±1 mm downstream of (i.e., above) the central tube.[1]

3.5.3.4. Spatial resolution shall be 0.15 mm or better. Resolution of 0.05 mm or better is preferred.[<1,<3,<4]

3.5.3.5. The measurements should be possible for regions with gas temperatures in the range of 1200-2100 K and soot volume fractions less than 0.1 ppm. NASA will provide the calibration data, but the investigators are responsible for the verification analysis.[<1,<3]

3.5.3.6. The measurements should have a precision of ±25 °C and an accuracy of ±50 °C. NASA will provide the calibration data, but the investigators are responsible for the verification analysis.[3]

3.5.3.7. Simultaneous measurement is desired on 5 or more lines, orthogonal to the chamber axis and preferably in the same plane, spaced 5 mm ±**TBD** (0.5 mm?) apart from the neighboring lines.[*,>3]

3.5.3.8. If the measurement is made by TFP, then the fiber(s) shall be 15-micron SiC fibers.[3]

3.5.3.9. If fibers are used, they shall be retractable with minimal disturbance to beyond 60 mm from the burner. Partial retraction for the purpose of soot burn-off is required (to be commanded by uplink prior to ignition).[3]

3.5.3.10. The sensor shall allow variable gain via uplink prior to ignition.[3]

3.5.3.11. The measurements shall occur at least every 5 s with a temporal resolution of 5 s.[3,<4]

3.5.3.12. The measurements shall start and stop according to uplink prior to ignition. *Not all the data will be saved.*[3]

3.5.4. <u>Far-Field</u>

SDEPs: 3A2; 3B2; 3C2; 4A3; 4B2,4; 4C2

3.5.4.1. Far-field temperatures shall be measured. *It is suggested that these temperatures will be measured with fine wire, exposed junction thermocouples. Other methods that meet the requirements also are acceptable.*[3,4]

3.5.4.2. Three measurements shall be made along unobstructed lines passing through the spherical burner at radii of 40, 50, and 60 mm, preferably within ±1 mm. All measurements shall avoid the region within 20 degrees of the burner supply tube.[<3]

3.5.4.3. Six additional measurements shall be made in three orthogonal directions, avoiding the region within 20 degrees of the burner supply tube. The measurements shall be made at radii of 100 and 200 mm from the center of the spherical burner, preferably within ±1 mm. The outer measurements shall be made at least 10 mm from the wall and the corresponding radial position can be reduced from 200 mm (e.g., by 10 mm) to avoid wall interference.[>4]

3.5.4.4. The range of the measurement shall be 100-1820 °C (40-50 mm positions), 0-1372 °C (60-100 mm positions) and 0-100 °C (near-wall station).[3]

3.5.4.5. The accuracies of the measurement shall be ±2 °C (40-50 mm positions), ±1 °C (60-100 mm positions) and ±0.2 °C (near-wall station).[3,>4]

3.5.4.6. The instrument response time should be as short as possible. *This could be accomplished by using fine wire, exposed junction thermocouples (potentially butt welded) with wire diameters that are as small as possible (e.g., 0.005 inch diameter) given other constraints. The fine wires should extend for at least 100 diameters in length from the junctions to minimize conductive heat transport.**

3.5.4.7. The measurements shall be made at 1 Hz or greater with a temporal resolution of 0.5 s.[3]

3.6. Soot Volume Fraction

SDEPs: 1B6-7,11-12; 2C1-4; 3A4; 3B4-5; 4A4; 4B2,4; 4C2,5

3.6.1. The soot volume fraction within the flame shall be measured. *It is suggested that it be measured by laser extinction using the HiBMs laser diode illumination package and the HiBMs camera followed by deconvolution. Other methods that meet the requirements also are acceptable.*[3]

3.6.2. For the **spherical flames**, the minimum measurement region shall be the region within 30 mm of the burner.[3]

3.6.3. For the **gas-jet and coflow flames**, the measurement region shall be the area within 10 mm of the burner axis (i.e., 20 mm diameter), centered on the burner axis, extending from the burner outlet to 25±1 mm downstream of (i.e., above) the central tube.

3.6.4. Spatial resolution should be 0.15 mm or better. Resolution of 0.05 mm or better is preferred.[<1,<3]

3.6.5. The measurements should be possible for regions with soot volume fractions in the range of 0.1-20 ppm, but verification is the investigators' responsibility.[<3]

3.6.6. The measurements should have a precision of ±0.01 ppm and an accuracy of ±0.05 ppm. NASA will provide the calibration data, but the investigators are responsible for the verification analysis. *The accuracy listed does not include contributions from uncertainty in the soot absorption function* $E(m)_\lambda$.[3]

3.6.7. There shall be a laser output power monitor. The sensor shall allow variable gain to compensate for instrument drift such that the image without flame is slightly below saturation.[3]

3.6.8. Three image types are required: laser, flame, and laser plus flame.[3]

3.6.9. The measurements shall be made at 1 Hz with a temporal resolution of 1 s.[3]

3.6.10. The measurements shall start and stop according to uplink prior to ignition. *Not all the data will be saved.*[3]

3.7. Radiant Emission

SDEPs: 4B4; 4C2-4

3.7.1. Flame radiant emissions shall be measured within ±10%. *It is suggested that the measurements be made using thermopile detectors (e.g., with KBr or BaF2 windows for a wide spectral range). Other approaches that meet the requirements are acceptable.*[4]

3.7.2. For the **spherical flames**, the detection region shall be the region within 60 mm of the burner.[3]

3.7.3. For the gas-jet and coflow flames, the detection region shall be the area within 10 mm of the burner axis (i.e., 20 mm diameter), centered on the burner axis, extending from the burner outlet to 25±1 mm downstream of (i.e., above) the central tube.[1]

3.7.4. The detector shall have a spectral range of 0.2-11 microns (to include CO2 and OH* emission), an irradiance range of 0.0001-0.1 W/cm^2, and a response time of 0.1 s or better.[<3,<4]

3.7.5. The detector shall be located near the chamber wall, preferably in the same plane as the CIR window centers.[3,*]

3.7.6. The radiant emission shall be measured at 60 Hz with a temporal resolution of **TBD**.[4,*]

3.8. Chemiluminescent Emission

SDEPs: 1A6; 2A5,7; 2B2-5; 2D1,3; 3C4-5; 4B1; 4C1,3-4

Flame extinction limits will be determined by a combination of two diagnostics: photomultiplier tube measurements and color imaging (see 3.1). It is envisioned that the requirements could be met with a set of three Hamamatsu H5784-03 photomultiplier tube (i.e., photosensor) modules. Other instruments or methods that meet the requirements, such as with a monochromator, are also acceptable.

3.8.1. Flame extinction shall be automatically detected and trigger the next sequence event.[2,3]

3.8.2. Measurement shall be made of the following spectra where the only difference between the three instruments should be the addition of a filter in the first two cases.

3.8.2.1. OH* chemiluminescence at 310 nm with a 10 nm or larger FWHM [3,*]

3.8.2.2. CH* chemiluminescence at 431 nm with a 10 nm or larger FWHM [3,*]

3.8.2.3. broadband emission from 300 (or less) to about 600 nm [3,4]

3.8.3. For the **spherical flames**, the detection region shall be the 120 mm diameter region centered on the spherical burner (or the intersection of the CIR chamber window axes).

3.8.4. For the **gas-jet and coflow flames**, the detection region shall be at least a 20-mm wide area, centered on the burner axis, extending from the burner outlet to 25±1 mm downstream (i.e., above) the central tube.[1,3]

1.1.1. The system shall have a sensitivity to flame radiation at least as good as that of the human eye, as verified in normal-gravity testing. *In 1g testing at NASA Glenn (conducted by Amy Mielke in 2001), the Hamamatsu H5784-06 was shown to be approximately one to two orders of magnitude more sensitive than the human eye where blue and yellow ethylene Santoro burner flames were viewed at a distance of about 120 mm.*[3]

1.1.2. The sensors should have a stable response in 1 second or less. *A quick response time is desired to account for ignition, when the gain might be reduced to avoid saturation (for example).**

1.1.3. The sensors shall allow variable gain via uplink prior to ignition.[3]

1.1.4. The measurements shall be made at a frequency of at least 120 samples/s and preferably at 1 kHz or faster, ideally with a frequency response that of 1k Hz or greater.[2-4]

1.2. Ion Current (E-FIELD Flames)

SDEPs: 2A1-8; 2B1-3,5; 2C1-5; 2D1,3-5

It is expected that the ion current will be measured indirectly by measuring the voltage drop across a current sense resistor of known value and computing $I = V/R_{sense}$. *This is how the measurement has been made in the ground-based testing.*

1.2.1. Ion current produced between the burner and mesh electrode shall be measured.[2]

1.2.2. The amplitude of the ion current measurement shall be over a range of at least 0 to 25 microamps, and preferably 0 to 50 microamps. *The direction of the ion current in the circuit depends of the mesh polarity.*[2]

1.2.3. The current leakage without a flame (in ambient air) shall be no more than 10 nanoamps at ±10 kV. *Ground-based testing has been conducted with leakage current that is this low.*[2]

1.2.4. The ion current should be measured with an error of no more than the larger of ±2% of the reading or ±0.02 microamps.[2]

1.2.5. The measurements shall be made at a frequency of at least 120 samples/s and preferably at least 100,000 samples/s, with a temporal resolution of 1 ms or less.[2]

1.3. Post-Test Gas Composition (Desired)

It is envisioned that these requirements could be met with the gas chromatograph (GC) developed for CIR, if it were delivered to ISS and installed. Alternately, the requirements could potentially be met by the multi-species fiber optic technology for simultaneous Raman detection of O2, N2, hydrocarbons, etc. developed at NASA Glenn by Viet Nguyen. This desired measurement is generally only of interest for the spherical flame tests.

1.3.1. Post-test analysis of the chamber gas composition is desired.[3]

1.3.2. The sampling location should be near the chamber wall along an unobstructed line from the spherical burner (or the intersection of the CIR chamber window axes).[3]

1.3.3. The concentrations of the following gases should be measured: CO, CO_2, CH_4, C_2H_2, C_2H_4, and N_2.[3]

1.3.4. Desired accuracies are ±0.01 mole fraction for N_2 and ±0.001 for CO, CO_2, CH_4, C_2H_2, and C_2H_4.[3]

1.3.5. It is desired that two samples should be taken, one immediately after extinction and the other after complete mixing of the chamber contents.[3]

2. Operational Requirements*

2.1. General Requirements

2.1.1. Uplink Command Parameters*

2.1.1.1.Flow activation, flow rates, and 2 ramp rates (e.g., slpm/min)
- 2.1.1.1.1. Fuel
- 2.1.1.1.2. Fuel diluent
- 2.1.1.1.3. Coflow oxidizer
- 2.1.1.1.4. Coflow diluent

2.1.1.2.Electric field control
- 2.1.1.2.1. Activation
- 2.1.1.2.2. DC vs. AC
- 2.1.1.2.3. Voltage
- 2.1.1.2.4. Voltage ramp rate
- 2.1.1.2.5. Frequency (for AC field)
- 2.1.1.2.6. Flame control parameters, **TBD** *(e.g., feedback gains)*

2.1.1.3.Ignition
- 2.1.1.3.1. Igniter activation
- 2.1.1.3.2. Igniter position
- 2.1.1.3.3. Igniter power

2.1.1.4.Chamber pressure

2.1.1.5.Chamber fan activation

2.1.1.6.Dynamic venting activation

2.1.1.7.Camera settings including exposure time and/or gain, image acquisition rates, settings for the liquid crystal tunable filter, etc.

2.1.1.8.Illumination package activation

2.1.1.9.Lamp activation

2.1.1.10. TFP fiber array position and translation rate

2.1.1.11. Gas chromatography (GC) activation (desired)

2.1.1.12. Test sequence timing
- 2.1.1.12.1. Igniter on-duration
- 2.1.1.12.2. Flow ramp #1 on and off times
- 2.1.1.12.3. Flow ramp #2 on and off times
- 2.1.1.12.4. TFP fiber array translation on and off times
- 2.1.1.12.5. Electric field on and off times
- 2.1.1.12.6. Voltage ramp on and off times
- 2.1.1.12.7. Image acquisition on and off times
- 2.1.1.12.8. Illumination package on and off times
- 2.1.1.12.9. Liquid crystal tunable filter times
- 2.1.1.12.10. Test duration

2.1.1.13. Data sampling rates

2.1.2. Downlink Data Requirements*

2.1.2.1.Digital Data

2.1.2.2. Image Data

2.1.3. Nominal Test Sequence*

	Fill chamber as needed
t-5	Mix atmosphere with chamber fan
t-4	Wait settling time to allow atmosphere to become quiescent
t-3	Translate the TFP array or mesh electrode (desired) to start position
t-2	Record reference images using lamp or illumination package, if desired
t-1	Activate diagnostics
t0	Initiate flows at ignition condition (incl. venting, if desired); ignite flame
t01	Wait briefly for ignition flame to stabilize
t02	Ramp burner flows at rate #1 to initial test condition
t03	Wait for flame to stabilize
t04	Translate the TFP array or mesh electrode (desired), if desired
t05	Activate electric field, if desired
t06	Ramp electric field voltage or activate electric field control, if desired
t07	Ramp burner flows at rate #2, if desired
t08	Stop burner flows, per extinction detection or test duration
t09	Stop data acquisition
	Select data for downlink
	Downlink data

2.2. Operational Sequences

2.2.1. CLD Flame

The main goal of this experiment is to evaluate flame characteristics at the extremes of fuel dilution: both weak, highly-dilute flames, and sooting flames up to pure-fuel conditions. While such parameters as the extinction limits and potential smoke points within these flames can easily be determined in normal gravity, we will not know the exact microgravity limits until the experiment is run on the ISS. We therefore plan to execute an initial run for each fuel where we vary the flow velocities and dilution levels in order to determine the extinction limits and degree of soot production in microgravity. For extinction limits, the flow velocity will be slowly ramped until extinction is observed for a given dilution level. The dilution level will then be increased in 5% increments and the procedure repeated. Extinction can be detected quickly with a PMT, but all three imaging systems will be run during these scans to maximize the data collected. For sooting determination, the dilution level will be decreased in 5% increments and/or the flow velocity will be increased in 5 cm/s increments until soot is observed, and then continued until either a smoke point is reached or a predetermined upper limit is reached. These observations can be made using color photography. The table below outlines the procedure to determine the extinction limits of the flames as well as identify any smoke points for the C_2H_4 flames. Based on the results of these scans, the exact test matrix can be modified as necessary for further runs.

Table 4.2.1.1

Exploratory test procedures to determine final test limits.	
Extinction Limit Test	**Approx. Start Time**
1. Prepare chamber atmosphere 2. Start coflow and fuel/inert flow at TBD ignition condition (e.g., a 40% CH_4 flame or a 20% C_2H_4 flame); begin active venting 3. Ignite flame and retract igniter 4. Slowly ramp flow (0.5 cm/s2) to starting velocity, if needed 5. Begin scan for a specific dilution: Increase velocity at a rate of 0.5 cm/s2 6. Stop test when extinction is detected by PMT or 50 cm/s is reached 7. Reduce fuel concentration by 5% and repeat steps 2-6 for the next dilution 8. Keep reducing fuel concentration by 5% and repeating steps 2-6 until minimum fuel concentration (see test matrix in Tables 4 and 5) is reached 9. Reset apparatus	0 sec. 10 sec. 20 sec. 30 sec. 110 sec.
Sooting Limit Test (for smoke point of ethylene flames)	
1. Prepare chamber atmosphere 2. Start coflow and fuel/inert flow at TBD ignition condition (e.g., a 40% C_2H_4 flame); begin active venting 3. Ignite flame and retract igniter 4. Ramp flow velocity (TBD) to 40% C_2H_4, 10 cm/s 5. Begin scan of 40% C_2H_4: Increase velocity at a rate of 0.5 cm/s2 6. Stop test when 35 cm/s is reached 7. Ramp flow velocity (TBD) to 45% C_2H_4, 10 cm/s 8. Begin scan of 45% C_2H_4: Increase velocity at a rate of 0.5 cm/s2 9. Stop test when the velocity reaches the smoke point determined in the previous run, or 35 cm/s 10. Repeat steps 7-9 for 50% C_2H_4 11. Repeat steps 7-9 for 50% C_2H_4, double fuel velocity 12. Reset apparatus	0 sec. 10 sec. 20 sec. 30 sec. 80 sec.

Due to the large number of conditions to be tested and the limited amount of gases available (as many as 50+ conditions for each fuel), it is necessary to minimize the test time, while exploring as many conditions as possible. One experimental concern involves the stabilization time necessary to change between different flow conditions, specifically when changing the ratio of fuel to inert. To minimize this time, the mixture ratio will be held fixed and the exit velocity will be varied. Varying the exit velocity has been observed to produce a steady flame within seconds. This improvement allows for data acquisition on the next test condition to begin without having to wait, minimizing the time necessary to navigate the range of flow conditions under investigation. Experiments in the coflow flame will be carried out in the order laid out in following table. They will follow one of two sequences: (a) varying flow conditions towards extinction, or (b) varying flow conditions to a sooting condition. First the chamber will be filled to a pressure of one atmosphere. Normal gravity tests of our 25 mm diameter coflow flames in an enclosed 43-liter chamber filled with argon indicate that the fill gas is not critical, since the coflow provides the local environment for the flame. However, under microgravity conditions, the flames could exhibit greater sensitivity to the fill gas. To investigate this, our first exploratory test for methane extinction will be carried out twice – once with cabin air from when the chamber is first sealed, and a second time with ambient nitrogen. Once the ambient environment is set, the igniter will be inserted, active venting will be initiated, and the coflow and fuel/inert flow will begin at predetermined ignition conditions. Once ignition is detected the igniter will be removed and the flow conditions set to the starting point of a particular experimental run. Ideally, the fuel dilution level used for a single run would also be used for ignition; however, in the more dilute cases removal of the igniter from the flame is anticipated to extinguish the flame. Therefore, those runs will begin in the moderately-dilute (or healthy) flame range for ignition purposes. The fuel dilution will be adjusted to the initial test case (if necessary) and then data acquisition will be carried out at the different fluid velocities until extinction is detected. Once the extinction limit is reached for a particular dilution level, the flow conditions will be reset to a healthy ignition setting and reignited.

Table 4.2.1.2

Coflow Laminar Diffusion Flame Overall Operational Sequence.	
Action	Approx. Start Time
1. Fill chamber to 1 atm	
2. Mix with chamber fan	-5 min.
3. Take reference images	-1 min
4. Start coflow and fuel/inert flow at ignition condition and start active venting	0 sec.
5. Ignite flame and retract igniter	10 sec.
6. Ramp flow velocity (TBD) to initial test condition, if needed	20 sec.
7. Wait for flame to stabilize	
8. Run data acquisition	30 sec.
9. Ramp flow velocity (TBD) to next test condition	45 sec.
10. Run data acquisition	55 sec.
11. Repeat 9 and 10 until (10 cases each run): a) the extinction limit b) the sooting extreme Limits determined from exploratory tests. Continue at next dilution for test duration	70 sec.
12. Extinguish flame	
13. Take reference images, if applicable	
14. Downlink data	
15. Reset apparatus	

The (a) and (b) sequences may require somewhat different exposure times, as chemiluminescence images (a) require up to 10 second exposure lengths, and soot luminosity images (b) will saturate in less than one second for highly sooting flames. During the sooting experiments, chemiluminescence images will still be acquired and will be the determining factor for the total amount of time necessary for data acquisition at each test condition. Since the exposures used for the soot luminosity images are so much shorter than the chemiluminescence images, it will be possible to take exposures at several settings of the tunable color filter (for multi-colored pyrometry) in the same span of time. Similarly, it will be possible to take data with both the laser on and laser off at each flame condition for laser extinction and to translate the TFP array through the flame. The general assumptions made in calculating the times required for recording a single flame condition are that it will take 15 seconds for a single data acquisition cycle and 10 seconds to change flow conditions and allow the flame to stabilize.

2.2.2. E-FIELD Flames

The E-FIELD experiment consists of 4 objectives corresponding to 4 series of tests using 2 different diffusion flame burner configurations. The first three test series provide the key fundamental information regarding the electrical character of diffusion flames and the influence of electric fields on soot formation; the final series focuses on electric field sensing and control of flames:

(A) Voltage sweep – collection of *VI curves (or VCC curves)* -- where the voltage is swept from 0-±10kV (or until flame blowout) and the ion current is monitored and recorded. The sweep can be a series of discrete steps, where a settling time is allowed after each voltage change. At the same time, color and OH* video records the flame shape and luminosity (both broadband flame and soot luminosity and OH* chemiluminescence) throughout the sweep. We prefer discrete steps in the sweep rather than a continuous ramp because we expect to need a system settling time and higher voltage resolution at some parts of the curve to effectively map the current transition points. A typical step sweep might comprise: 15 second ignition & stabilization; 200 V/step, 0.1 sec ion current measurement, 2 sec settle between steps, and a second 0.1 sec ion current measurement at each point, to ±10kV or blowout. It is important to keep in mind that the 2.2 seconds per test point is only possible because the changes are developing from a prior quasi-steady condition. If tests were attempted with a pair of voltage steps from a zero voltage initial condition (as in a drop test, for example), the settling time would more than double. Blowout can be detected by a sharp drop in ion current. We plan for 2 repeats per curve at selected conditions (noted in test matrix), and positive and negative potential sweeps are included. Expected run times are 160 seconds per sweep (including a background current sweep with the flame off), 600 seconds per set maximum (including both polarities, flame off, and repeats). An example of this kind of data was shown in Figures 1.10 and 2.2 for the ion current and Figures 1.5, 1.13, and 2.1 for the images. If available, density imaging will provide thermal field information at each voltage step during a 70 second sweep when the flame is on.

(B) ***Step response***—where the voltage is changed rapidly from a base level to a much higher (or lower) level and the ion current (and flame luminosity and shape) is monitored in time as it settles to its new steady value. The key measurable is the ion current as a function of time just following the voltage step change. As in the test set (1), video, luminosity, and chemiluminiscence will record these flame behaviors in response to an instantaneous change in the electric field. A typical experiment sequence might comprise 15 second ignition and stabilization; 600 V step change, record ion current for 3 seconds between step changes; 10 base voltages --example could be 0-4500 V in 500 V increments, 2 repeats per set, 30 seconds per set, 300 seconds per condition maximum. The two test series described above are carried out for a broad range of burner conditions (using up to 2 gas jet nozzles and the co-flow burner; fuel type variations between CH_4 and C_2H_4; and nitrogen dilution level of the fuel), and they provide the foundation information necessary to create an electrodynamic model of the flame. The control input signals are flame luminosity (luminosity and CH* chemiluminscence) and ion current. Correlations between these two signals will also be examined. Once the dynamics of the flame has been determined from the VCC curves and the step response data, examination and control of soot luminosity using electric fields will be performed. Finally, we will use electric fields to control flame liftoff height and extend blowout limits in the co-flow burner.

(C) ***Electric field effects on soot*** – demonstrate effects of the electric field on soot
(measured by broadband emission from the flame and soot volume fraction) by turning on and off the field under the appropriate conditions derived from experiments (1) and (2) above (time details: depends on the burner, but each test will be allowed at least 1 minute). Both broad solid angle collection luminosity

and flame images will be used to determine the sooting behavior, along with soot volume fraction and soot pyrometry measurements for quantitative analysis.

(D) ***Open loop control*** – demonstrate control of the flame liftoff height and blowoff conditions using the electric field by turning on and off the field under the appropriate conditions derived from experiments (A) and (B) above (time details: depends on the condition, but each test will be allowed at least 1 minute). Voltage source capable of ±10kV desired. Ion current and luminosity (broadband and CH*) fluctuations will be used to determine the flame's approach to blowoff, and flame images will be used to determine the liftoff height. Note that fuel dilution with an inert may be necessary to allow flames to reach appropriate blowout conditions within experiment limitations; these conditions will be determined during the above test series and from the complementary results from the CLD Flame experiment.

General Operations

Before any of the electric field experiments, the high voltage mesh should be installed (or moved into position). Leak current should be measured by sweeping the voltage from 0 to 10kV and 0 to -10kV with no flame present. A steep rise in current under these conditions indicates corona discharge and sets the upper limit on the potential. The test sequence involves a complete repeat voltage sweep with no flame to provide a point-by-point current leak measurement. A similar sweep should be completed following flame extinguishment at the end of a test set. The leak current allows a baseline for higher precision in the flame ion current determination. In addition, excessive leak current at relatively low voltage may indicate electron emission from carbon buildup on the gas jet flame tip. If the leak current exceeds 10% of the flame ion current, cleaning of the gas jet tip is requested. Cleaning consists of a manual wiping or possibly burning off the carbon with a modified flame condition. We expect this to be a rare request, but the continuous monitor of flameless ion current provides a reliable in-situ monitor. We assume that the chamber will be emptied and refilled approximately every 7-8 tests to minimize the oxygen concentration uncertainty in the test chamber. We further assume that our test series will start with the co-flow burner if it is already installed to minimize replacement time. After the co-flow experiments, a gas jet burner would be installed. The gas jet flame experiments duplicate our laboratory-based studies. The exact times for settling and voltage steps may vary (they should be reconfigurable from the ground), but a nominal expected operational sequence for one chamber fill and the key measurement data sets are shown below.

Table 4.2.2.1

Voltage Sweep Procedure	
Action	**Approx. Start Time**
A. Prepare Chamber	
1. Fill chamber (with N_2 for coflow; O_2/N_2 for gas jet)	
2. Select fuel/diluent mixture	
B. Initiate Experiment	
1. Initiate data acquisition	
2. Initiate gas flows	0 s
3. Ignite flame and retract igniter.	0 s
4. Allow 10 seconds settling time.	3 s
5. Set the desired voltage (initially to 0V)	13 s
6. Initiate high voltage power supply	14 s
C. Measurements	
1. Collect data over 0.1 seconds	15 s
2. Wait 2 seconds (or continue to collect data)	17 s
3. Collect data over 0.1 seconds	17 s
D. Step 200V	18 s
E. Repeat steps C & D until maximum or flame blowout	160 s
F. Pause in Experiment	
1. Stop gas flows/extinguish flame (zero ion current)	
2. Stop video	
3. Zero voltage	
G. Repeat Steps C-E without flame to measure leakage current. Stop testing if burner current leakage is at unacceptable level	
H. Downlink data	
I. Reverse high voltage polarity	
J. Repeat entire sequence steps (B)–(H)	

Table 4.2.2.2

Voltage Step Procedure	
Action	**Approx. Start Time**
A. Prepare Chamber	
1. Fill chamber (with N_2 for coflow; O_2/N_2 for gas jet)	
2. Select fuel/diluent mixture	
B. Initate Experiment	
1. Initiate data acquisition	
2. Start gas flows	0 s
3. Ignite flame and retract igniter	0 s
4. Allow 10 seconds settling time	3 s
5. Set the desired voltage (initially to 0V)	13 s
6. Initiate high voltage power supply	14 s
C. Measurements (if blowout occurs anytime; zero voltage and proceed to Step D)	
1. Collect data over 1.5 second	15 s
2. Step voltage + 600V to 600V; Collect data over 1.5 second	16.5 s
3. Step voltage -100V to 500V; Collect data over 1.5 second	18 s
4. Step voltage +600V to 1100V; Collect data over 1.5 second	19.5 s
5. Step voltage -100V to 1000V; Collect data over 1.5 second	21 s
6. Step voltage +600V to 1600V; Collect data over 1.5 second	22.5 s
7. Step voltage -100V to 1500V; Collect data over 1.5 second	24 s
8. Step voltage +600V to 2100V; Collect data over 1.5 second	25.5 s
9. Step to 2000V; Collect data as above	27 s
10. Step to 2600V; Collect data as above	28.5 s
11. Step to 2500V; Collect data as above	30 s
12. Step to 3100V; Collect data as above	31.5 s
13. Step to 3000V; Collect data as above	33 s
14. Step to 3600V; Collect data as above	34.5 s
15. Step to 3500V; Collect data as above	36 s
16. Step to 4100V; Collect data as above	37.5 s
17. Step to 4000V; Collect data as above	39 s
18. Step to 4600V; Collect data as above	40.5 s
19. Step to 4500V; Collect data as above	42 s
20. Step to 5100V; Collect data as above	43.5 s
21. Step to 5000V; Collect data as above	45 s
22. Step to 0V; Collect data as above	46.5 s
D. Shut off gas flows (extinguish flame)	48 s
E. Repeat Step C beginning from 0V without flame to measure leakage current. Stop testing and report if leakage is at unacceptable level	
F. Downlink data	
G. Reverse high voltage polarity	
H. Repeat entire sequence steps (B)–(E)	

Note that the final step to zero (C.22) with the flame on has a 1.5 second measurement to determine any variation from the initial zero voltage flame on condition. There is a following 1.5 second measurement at zero voltage with the flame extinguished that precedes the leakage current sequence.

Soot Effects and Control Experiments

The experiments associated with control will be defined based on the results of the above baseline mapping experiments. After completing and evaluating the results, there are two sets of control experiments to be accomplished. The first is an open loop attempt to control the soot and the second is to extend the blowout limits of the co-flow flame. We will use the findings of the first two test series and the CLD Flame experiment to identify the conditions of flame sensitivity. The procedure is a series of voltage ramps (or small steps with continuous data collection); just to be sure there is no confusion at the end of the sequence, each step is identified but hopefully the pattern is clear.

Table 4.2.2.3

Soot Effects and Control Experiments Procedure	
Action	**Approx. Start Time**
A. Prepare Chamber	
1. Fill chamber (with N_2 for coflow; O_2/N_2 for gas jet)	
2. Select fuel/diluent mixture	
B. Initate Experiment	
1. Initiate data acquisition	
2. Start gas flows	0 s
3. Ignite flame and retract igniter	0 s
4. Allow 10 seconds settling time	3 s
5. Set the desired voltage (initially to 0V)	13 s
6. Initiate high voltage power supply	14 s
C. Collect reference data for 1 second	15 s
D. Set voltage to V*, the initial (lifted or sooting) condition identified in prior tests	16 s
E. Measurements	
1. Collect data over 1 second	16 s
2. Step voltage -300V to V*-300V; Collect data over 1.0 second	17 s
3. Ramp at +100V/s (or step +50V) while collecting data over 0.5 s	18 s
4. Collect data at V*-250V over 1.0 second	18.5 s
5. Ramp at +100V/s (or step +50V) while collecting data over 0.5 s	19.5 s
6. Collect data at V*-200V over 1.0 second	20 s
7. Ramp at +100V/s (or step +50V) while collecting data over 0.5 s	21 s
8. Collect data at V*-150V over 1.0 second	21.5 s
9. Ramp at +100V/s (or step +50V) while collecting data over 0.5 s	22.5 s
10. Collect data at V*-100V over 1.0 second	23 s
11. Ramp at +100V/s (or step +50V) while collecting data over 0.5 s	24 s
12. Collect data at V*-50V over 1.0 second	24.5 s
13. Ramp at +100V/s (or step +50V) while collecting data over 0.5 s	25.5 s
14. Collect data at V* over 1.0 second	26 s
15. Ramp at +100V/s (or step +50V) while collecting data over 0.5 s	27 s
16. Collect data at V*+50V over 1.0 second	27.5 s
17. Ramp at +100V/s (or step +50V) while collecting data over 0.5 s	28.5 s
18. Collect data at V*+100V over 1.0 second	29 s
19. Ramp at +100V/s (or step +50V) while collecting data over 0.5 s	30 s
20. Collect data at V*+150V over 1.0 second	30.5 s
21. Ramp at +100V/s (or step +50V) while collecting data over 0.5 s	31.5 s
22. Collect data at V*+200V over 1.0 second	32 s
23. Ramp at +100V/s (or step +50V) while collecting data over 0.5 s	33 s
24. Collect data at V*+250V over 1.0 second	33.5 s
25. Ramp at +100V/s (or step +50V) while collecting data over 0.5 s	34.5 s
26. Collect data at V*+300V over 1.0 second	35 s
27. Step to 0; collect data for 2 seconds	36 s
F. Stop gas flows/extinguish flame	38 s
G. Repeat Steps D-E with no flame to determine current leakage	
H. Downlink data	

* - Voltage level determined to affect soot or liftoff from previous experiments
Note: return to step B and reignite as needed if flame fails during experiment

The sequence would then repeat Steps B-H for following cases with given fuel/diluent mixture and change mixture as required. For the gas jet burner, open loop exploration will be allowed five minutes of total run time, and four conditions will be examined for soot control. For the co-flow burner, open loop exploration will be allowed 10 minutes of total run time, and eight conditions will be examined, four for soot control and four for liftoff/blowout.

2.2.3. Flame Design

The Flame Design operational sequences are summarized in the numbered steps below.

Table 4.2.3.1

Operational Sequence for Spherical Flame Tests	
Action	Approx. Start Time
1. Verify that the intended compressed gas bottles are installed. Preflow the burner fluent gas at the composition of the upcoming test point to flush the plumbing system. 2. Establish chamber conditions. These consist of a set point pressure and species compositions, as specified in the test matrix (Table A.1). Conditions are obtained in four ways: from cabin air (S1); from the preceding test (e.g., S2); from scrubbing and replenishing (e.g., S9-11); or from a complete evacuation and recharge (e.g., S6-8). 3. Allow chamber contents to reach equilibrium. A hold time of 5 minutes is required for quiescent, isothermal, and well-mixed conditions. 4. Take reference images (if applicable). Begin color imaging at 30 Hz. Begin monitoring measurements. After 15 s, commence fluent flow (normally at 1.5 mg/s fuel flow rate), ignite flame, and retract ignitor. The start of flow is defined as $t = 0$. 5. Allow the flame to pass its soot-inception limit (at approximately $t = 15$ s). This will normally be accomplished without any change in fluent flow rate. Continuously record temperature distributions. 6. Allow the flame to pass its radiative extinction limit (at approximately $t = 30$ s). This will normally be accomplished without any change in fluent flow rate. Continuously record temperature distributions. At TBD (estimated 3 s) after extinction detection, reduce flow rate by TBD (estimated 50%) for TBD (estimated 5 s) to confirm extinction. (If the flame reappears, return to the initial flow rate and start Step 6 again.) Terminate the fluent flow. Record reference images (if applicable). After 60 s terminate color imaging and monitoring measurements. Select data for downlink and downlink data. 7. Perform kinetic extinction test as follows. Repeat Steps 3 and 4 above. After a TBD delay (predetermined), decrease fluent flow rate (at fixed composition) linearly in time such that flow rate becomes zero at TBD (estimated 30 s) after ignition. Allow the flame to pass its kinetic extinction limit. Continuously record temperature distributions. At TBD (estimated 3 s) after extinction detection, increase flow rate by TBD (estimated 100%) for TBD (estimated 5 s) to confirm extinction. (If the flame reappears, return to the initial flow rate and start Step 6 again.) Record reference images (if applicable). After 60 s terminate color imaging and monitoring measurements. Select data for downlink and downlink data. Return to Step 1.	

Table 4.2.3.2

Operational Sequence for Coflow Flame Tests

Action	Approx. Start Time
1. Verify that the intended compressed gas bottles are installed. Preflow the inner and outer jet gases at the composition of the upcoming test point to flush the plumbing system. 2. Establish chamber conditions, normally N_2 at a set point pressure. Conditions are obtained in two ways: from scrubbing and replenishing; or from a complete evacuation and recharge (TBD pending engineering input). 3. Allow chamber contents to reach equilibrium. A hold time of 5 minutes is required for quiescent, isothermal, and well-mixed conditions. 4. Take reference images (if applicable). Begin color imaging at 30 Hz. Begin monitoring measurements. After 15 s, commence inner and outer jet flow (flow rates TBD), initiate dynamic venting, ignite flame, and retract ignitor. Adjust inner jet flow rate for a luminous flame length of approximately 20 mm, based on experimental and computational correlations. 5. Use a slow ramp (ramp rate TBD) on inner jet inert flow rate. This will allow a quasisteady flame at its half-blue soot limit to be observed in the video record after the test. Continuously record temperature distributions for a time of TBD (estimated 30 s). 6. Terminate fluent flow. Record reference images (if applicable). After 60 s terminate color imaging and monitoring measurements. Select data for downlink and downlink data.	

2.2.4. s-Flame

Table 4.2.4.1

s-Flame Operational Sequence	
Action	Approx. Start Time
I. Establish chamber at constant pressure and species concentration. II. Discharge fuel mixture through porous burner at the initial flow rate. III. Ignite fuel mixture with hot wire coil and retract upon successful ignition. IV. Allow for spherical diffusion flame to evolve. V. Apply one of the following: a. Maintain flow rate with same initial mixture for duration of test (25 s) or until extinction. b. Single step decrease in flow rate with same initial mixture at specified time, maintaining new flow rate for duration of test (25 s) or until extinction. VI. Terminate fuel supply to the burner after 25s.	0 s 0 s 25 s

The proposed flight experiment plan maximizes the value of a single test by satisfying multiple scientific objectives. The priority of the scientific objectives to be examined are ordered for both non-sooty and sooty flames:

*(**A**) Transient phenomenon leading toward steady flame*
*(**B**) Extinction phenomenon at "quasi-steady"-states*
*(**C**) Instability phenomenon, e.g. Le > 1 oscillations and Le < 1 wrinkling*

*By ignition with the flame not situated at the steady flame location, we will automatically observe (**A**). In studying (**B**), we may perhaps observe (**C**). So objectives (**A**), (**B**), and (**C**) may all be addressed by conducting a single experiment.*

3. Test Matrices

3.1. CLD Flame

Once the full range of flow conditions to investigate has been determined using the initial exploratory procedure to establish extinction and sooting smoke-point limits, the plan for additional test cases will be finalized. Test matrices detailing the range of flames to be tested in the exploratory tests are provided in next three tables. Exploratory tests to determine the extinction limits of CH_4 and C_2H_4 are provided in Tables 5.1.1 and 5.1.2, respectively. Table 5.1.3 presents the tests to determine the smoke points (if any) of the C_2H_4 flames. Table 5.1.4 outlines a detailed preliminary test matrix for the CH_4 flames, and Table 5.1.5 outlines a detailed preliminary test matrix for the C_2H_4

flames. These test matrices have been laid out using observations of these flames at normal gravity coupled with the expectation that there will be a wider range of flames that can be stabilized under microgravity conditions.
Experimental runs have been split up into groups of ~10 tests so that a run will last ~4-5 min. Dilution levels with fewer test cases have been grouped together in an effort to minimize the number of time the experimental apparatus will have to be reset.

Table 5.1.1

Test matrix for exploratory tests of the extinction limits of methane.
Burner: coflow
Flow velocity: 15 cm/s to 50 cm/s for both nozzle and coflow (i.e., matched)
Test type: extinction detection
To verify the insensitivity of the flames to the ambient environment, this will be carried out twice – once with cabin air from when the chamber is first sealed, and a second time with ambient nitrogen.

Run	Test #	% CH4 (%N2)	Comments
A	1	40% (60%)	Initial run; ambient will be cabin air. Chemiluminescence will be monitored using a PMT to determine the velocity that causes extinction at this dilution level. The flow velocity will begin at 15 cm/s and will be ramped slowly at 0.5 cm/s2 until extinction is detected, or 50 cm/s is reached.
	2	35% (65%)	Same as above.
	3	30% (70%)	Same as above.
	4	25% (75%)	Same as above.
	5	20% (80%)	Same as above.
	6	15% (85%)	Same as above. *There may not be a stable flame at this dilution level.*
B	1	40% (60%)	Duplicate run; ambient will be nitrogen. 50 cm/s detection Chemiluminescence will be monitored using a PMT to determine the velocity that causes extinction at this dilution level. The flow velocity will begin at 15 cm/s and will be ramped slowly at 0.5 cm/s2 until extinction is detected, or 50 cm/s is reached.
	2	35% (65%)	Same as above.
	3	30% (70%)	Same as above.
	4	25% (75%)	Same as above.
	5	20% (80%)	Same as above.
	6	15% (85%)	Same as above. *There may not be a stable flame at this dilution level.*

Table 5.1.2

Test matrix for exploratory tests of the extinction limits of ethylene. Burner: coflow Flow velocity: 10 cm/s to 50 cm/s for both nozzle and coflow (i.e., matched) Test type: extinction detection			
Run	**Test #**	**% C2H4 (%N2)**	**Comments**
C	1	20% (80%)	Chemiluminescence will be monitored 50 cm/s detection using a PMT to determine the velocity that causes extinction at this dilution level. The flow velocity will begin at 10 cm/s and will be ramped slowly at 0.5 cm/s2 until extinction is detected, or 50 cm/s is reached.
	2	15% (85%)	Same as above.
	3	10% (90%)	Same as above. *There may not be a stable flame at this dilution level.*

Table 5.1.3

Test matrix for exploratory tests of the smoke points of ethylene. Burner: coflow Flow velocity: 10 cm/s to 35 cm/s for both nozzle and coflow (i.e., matched) Test type: smoke point detection			
Run	**Test #**	**% C2H4 (%N2)**	**Comments**
D	1	40% (60%)	The sooting tendency of the flames 35 cm/s detection will be monitored with color photography. The flow velocity will begin at 10 cm/s and will be ramped slowly at 0.5 cm/s2 until 35 cm/s is reached.
	2	45% (55%)	The sooting tendency of the flames 35 cm/s detection will be monitored with color photography. The flow velocity will begin at 10 cm/s and will be ramped slowly at 0.5 cm/s2 until 35 cm/s is reached, or to the smoke point observed in the previous run.
	3	50% (50%)	Same as above.
	4	50% (50%) (double-velocity fuel flow)*	*Same as above, but in this test, the flow velocity of the fuel and inert are doubled. The coflow is still run at the velocity listed.

Table 5.1.4

Test matrix for methane.
Burner: coflow
Note: v(bo) is the velocity at blow off determined from exploratory tests

Run	Test #	% CH4 (%N2)	Velocity (cm/s)	Test Type	Comments
1	1 2 3 4 5 6 7 8 9 10	15% (85%)	10 15 20 25 30 v(bo)-4 v(bo)-3 v(bo)-2 v(bo)-1 v(bo)-0.5	extinction/ lifted	REQUIRED Chemiluminescence will be monitored to determine the lift-off height and extinction limit. Tests may be removed from (or added to) this run based on the initial exploratory test. *There may not be a stable flame at this dilution level.*
2	11 12 13 14 15 16 17 18 19 20	20% (80%)	10 15 20 25 30 v(bo)-4 v(bo)-3 v(bo)-2 v(bo)-1 v(bo)-0.5	extinction/ lifted	REQUIRED Chemiluminescence will be monitored to determine the lift-off height and extinction limit. Tests may be removed from (or added to) this run based on the initial exploratory test.
3	21 22 23 24 25 26 27 28 29 30	30% (70%)	10 15 20 25 30 v(bo)-4 v(bo)-3 v(bo)-2 v(bo)-1 v(bo)-0.5	extinction/ lifted	REQUIRED Chemiluminescence will be monitored to determine the lift-off height and extinction limit. Tests may be removed from (or added to) this run based on the initial exploratory test.
4	31 32 33 34 35	40% (60%)	15 20 25 30 35	dilute/ lifted	HIGHLY DESIRED Chemiluminescence will be monitored to determine the lift-off height and flame shape as a function of velocity. Smaller velocity increments may be added for the 40% (60%) flame.
	36 37 38 39	50% (50%)	20 25 30 35		
5	40 41 42	60% (40%)	25 30 35	moderate/ lifted	DESIRED Chemiluminescence will be monitored to determine the lift-off height and flame shape as a function of velocity.
	43 44 45	65% (35%)	25 30 35		
	46 47 48	70% (30%)	25 30 35		
6	49 50 51	80% (80%)	25 30 35	sooting	REQUIRED The transition towards sooting will be monitored as the fluid velocity is increased and the dilution level decreased.
	52 53 54	90% (10%)	25 30 35		
	55 56 57	100% (0%)	25 30 35		

Table 5.1.5

Test matrix for ethylene. Burner: coflow Note: v(bo) is the velocity at blow off determined from exploratory tests					
Run	Test #	% C2H4 (%N2)	Velocity (cm/s)	Test Type	Comments
7	58 59 60 61 62 63 64 65 66 67	10% (90%)	10 15 20 25 30 v(bo)-4 v(bo)-3 v(bo)-2 v(bo)-1 v(bo)-0.5	extinction/ lifted	REQUIRED Chemiluminescence will be monitored to determine the lift-off height and extinction limit. Tests may be removed from (or added to) this run based on the initial exploratory test.
8	68 69 70 71 72 73 74 75 76 77	15% (85%)	10 15 20 25 30 v(bo)-4 v(bo)-3 v(bo)-2 v(bo)-1 v(bo)-0.5	extinction/ lifted	REQUIRED Chemiluminescence will be monitored to determine the lift-off height and extinction limit.
9	78 79 80 81 82 83 84 85 86 87	20% (80%)	10 15 20 25 30 v(bo)-4 v(bo)-3 v(bo)-2 v(bo)-1 v(bo)-0.5	dilute/ lifted	HIGHLY DESIRED Chemiluminescence will be monitored to determine the lift-off height and extinction limit.
10	88 89 90 91 92 93	30% (70%)	10 15 20 25 30 35	moderate/ lifted	DESIRED Chemiluminescence will be monitored to determine the lift-off height and flame shape as a function of velocity.
	94 95 96 97 98 99	40% (60%)	10 15 20 25 30 35		
11	100 101 102 103 104 105	50% (50%)	10 15 20 25 30 35	sooting	REQUIRED The transition towards sooting will be monitored as the fluid velocity is increased and the dilution level decreased. * In test #'s 106-111 above, the flow velocity of the fuel and inert are doubled to twice the value listed in the "Velocity" column. The coflow is still run at the velocity listed.
	106 107 108 109 110 111	50% (50%) (double-velocity fuel flow)*	10 15 20 25 30 35		

The test matrices presented above were created with two goals in mind: to investigate weak, dilute flames as they approach extinction, and to investigate the sooting *tendencies of richer flames. In all cases, flames are lifted off the burner surface so that heat transfer to the burner can be neglected in the computations. This approach has been observed to work well for all cases of the methane flames, whereas moderate heating of the burner surface has been observed for some cases of the ethylene flames. The laminar flame speed of ethylene is higher than that of methane, causing lift-off heights to decrease by approximately a factor of two. For nonsooting flames, this decrease in lift-off height does not create any burner heating. However, the more heavily sooting cases have been observed to cause moderate heat transfer to the burner, which becomes a problem in the ethylene flames since they have a higher propensity to soot, particularly at microgravity. The 50% C_2H_4 / 50% N_2 flame has been observed to be the lowest level of dilution that ensures the room temperature boundary condition at the burner surface to be a good assumption for the computations. By increasing the fuel flow rate by a factor of 2 (as shown in Test #'s 106-111 in Table 5.1.5), the overall amount of soot and the size of the sooting region are increased (at 1 g), with the sooting region substantially higher off the burner surface to prevent burner heating. Raising the sooting region further off the burner surface becomes more important under microgravity conditions as the lift-off height decreases relative to 1 g conditions due to the increased importance of axial diffusion.*

3.2. E-FIELD Flames

The two burners to be used are: (a) a simple gas jet nozzle with 2 sizes, 1.3 mm (required) and 2.1 mm diameter (desired), and (b) a co-flow burner (same as in the CLD Flame study). The former size matches our ground-based configuration and the latter size matches the inner fuel tube of the co-flow burner. Some of the conditions in the coflow burner test matrix intentionally match those proposed in the CLD Flame experiment to allow for future coordination and comparison. In all of the studies, the limiting commodity is oxygen for the system because the fuel use is very low in virtually all cases. There are four basic experimental activities involving electric field effects (VCC curves, voltage step changes, soot response, and stability behavior response). The conditions for the latter two depend on the findings in the former two, and so the test matrix is not definitive for these. Below is a table briefly summarizing the tests and the purpose of each. More details in this regard are in Section 2 under the description of the science data end products. Nominal and itemized test conditions planned for the co-flow burner and gas jet flames are in the table at the end of the E-FIELD Flames SRD. Specific test conditions may be altered, based on additional 1-g experiments.

Table 5.2.1

Test type	Test Purpose
VI curves: 1.35 mm gas jet; 2.13 mm gas jet; co-flow burner; two fuels; 4 dilution conditions; 3 flow rates.	Identify flame shape changes, ion current per unit flame area, saturation current for fuel and dilution conditions, relationship between luminosity and electric field strength
Step Response: 1.35 mm gas jet; 2.13 mm gas jet; co-flow burner; two fuels; 4 dilution conditions; 3 flow rates.	Determine time response of the flame to sudden changes in electric field; provides the dynamic model for the flame to be used in control loops.
Soot Formation: One gas jet and co-flow burner; 2 fuels; 2 dilution conditions	Determine response of soot to electric fields; distinguish ion wind effects from direct chemi-ion influences; evaluate soot contribution to ion current; demonstrate the ability of electric fields to control soot.
Blowout/stability control: co-flow burner; 2 fuels; 2 dilution conditions	Identify sensitive regions with the operating map where the electric field can change liftoff and stability behavior.

Table 5.2.2

Test Matrix: Gas Jet Flames - Required Tests

Burner: 1.35-mm gas-jet nozzle

Test #	**Fuel**	**% Fuel (% N2)**	**Nozzle flow (sccm)**	**Coflow (sccm)**	**Test Type**
GR1 GR2	CH_4	100% (0%)	30	n/a	Voltage sweep Step response
GR3 GR4		30% (70%)			Voltage sweep Step response
GR5 GR6		50% (50%)			Voltage sweep Step response
GR7 GR8		70% (30%)			Voltage sweep Step response
GR9 GR10		70% (30%)			Field effects on soot **TBD**
GR11 GR12		30% (70%)			Field effects on soot **TBD**
GR13 GR14		100% (0%)	40		Voltage sweep Step response
GR15 GR16		30% (70%)			Voltage sweep Step response
GR17 GR18		50% (50%)			Voltage sweep Step response
GR19 GR20		70% (30%)			Voltage sweep Step response
GR21 GR22		100% (0%)	50		Voltage sweep Step response
GR23 GR24		30% (70%)			Voltage sweep Step response
GR25 GR26		50% (50%)			Voltage sweep Step response
GR27 GR28		70% (30%)			Voltage sweep Step response
GR29 GR30	C_2H_4	100% (0%)	30		Voltage sweep Step response
GR31 GR32		30% (70%)			Voltage sweep Step response
GR33 GR34		50% (50%)			Voltage sweep Step response
GR35 GR36		70% (30%)			Voltage sweep Step response
GR37 GR38		100% (0%)	40		Voltage sweep Step response
GR39 GR40		30% (70%)			Voltage sweep Step response
GR41 GR42		50% (50%)			Voltage sweep Step response
GR43 GR44		70% (30%)			Voltage sweep Step response
GR45 GR46		100% (0%)	50		Voltage sweep Step response
GR47 GR48		30% (70%)			Voltage sweep Step response
GR49 GR50		50% (50%)			Voltage sweep Step response
GR51 GR52		70% (30%)			Voltage sweep Step response

Table 5.2.3

Test Matrix: Gas Jet Flames - Desired Tests Burner: 2.13-mm gas-jet nozzle					
Test #	**Fuel**	**% Fuel (% N2)**	**Nozzle flow (sccm)**	**Coflow (sccm)**	**Test Type**
GD1 GD2	CH4	100% (0%)	30	n/a	Voltage sweep Step response
GD3 GD4		30% (70%)			Voltage sweep Step response
GD5 GD6		50% (50%)			Voltage sweep Step response
GD7 GD8		70% (30%)			Voltage sweep Step response
GD9		70% (30%)			Field effects on soot
GD10		30% (70%)			Field effects on soot
GD11 GD12		100% (0%)	40		Voltage sweep Step response
GD13 GD14		30% (70%)			Voltage sweep Step response
GD15 GD16		50% (50%)			Voltage sweep Step response
GD17 GD18		70% (30%)			Voltage sweep Step response
GD19 GD20		100% (0%)	50		Voltage sweep Step response
GD21 GD22		30% (70%)			Voltage sweep Step response
GD23 GD24		50% (50%)			Voltage sweep Step response
GD25 GD26		70% (30%)			Voltage sweep Step response
GD27 GD28	C2H4	100% (0%)	30		Voltage sweep Step response
GD29 GD30		30% (70%)			Voltage sweep Step response
GD31 GD32		50% (50%)			Voltage sweep Step response
GD33 GD34		70% (30%)			Voltage sweep Step response
GD35		70% (30%)			Field effects on soot
GD36		30% (70%)			Field effects on soot
GD37 GD38		100% (0%)	40		Voltage sweep Step response
GD39 GD40		30% (70%)			Voltage sweep Step response
GD41 GD42		50% (50%)			Voltage sweep Step response
GD43 GD44		70% (30%)			Voltage sweep Step response
GD45 GD46		100% (0%)	50		Voltage sweep Step response
GD47 GD48		30% (70%)			Voltage sweep Step response
GD49 GD50		50% (50%)			Voltage sweep Step response
GD51 GD52		70% (30%)			Voltage sweep Step response

Table 5.2.4

Test Matrix: Coflow Flames - Required Tests
Burner: coflow

Test #	Fuel	% Fuel(% N2)	Nozzle flow (sccm)	Coflow (sccm)	Test Type
CR1 CR2	CH4	100% (0%)	30	0	Voltage sweep Step response
CR3 CR4		30% (70%)			Voltage sweep Step response
CR5 CR6		50% (50%)			Voltage sweep Step response
CR7 CR8		70% (30%)			Voltage sweep Step response
CR9 CR10		100% (0%)		4870	Voltage sweep Step response
CR11 CR12		30% (70%)			Voltage sweep Step response
CR13 CR14		50% (50%)			Voltage sweep Step response
CR15 CR16		70% (30%)			Voltage sweep Step response
CR17 CR18		30% (70%)			Field effects on soot Open loop control
CR19 CR20		70% (30%)			Field effects on soot Open loop control
CR21		100% (0%)	40	6493	Voltage sweep
CR22		30% (70%)			Voltage sweep
CR23		50% (50%)			Voltage sweep
CR24		70% (30%)			Voltage sweep
CR25 CR26	C2H4	100% (0%)	30	0	Voltage sweep Step response
CR27 CR28		30% (70%)			Voltage sweep Step response
CR29 CR30		50% (50%)			Voltage sweep Step response
CR31 CR32		70% (30%)			Voltage sweep Step response
CR33 CR34		100% (0%)		4870	Voltage sweep Step response
CR35 CR36		30% (70%)			Voltage sweep Step response
CR37 CR38		50% (50%)			Voltage sweep Step response
CR39 CR40 CR41 CR42		70% (30%)			Voltage sweep Step response Field effects on soot Open loop control
CR43 CR44		30% (70%)			Field effects on soot Open loop control

Table 5.2.5

Test Matrix: Coflow Flames - Desired Tests Burner: coflow					
Test #	**Fuel**	**% Fuel (% N2)**	**Nozzle flow (sccm)**	**Coflow (sccm)**	**Test Type**
CD1	CH4	100% (0%)	40	0	Step response
CD2		30% (70%)			Step response
CD3		50% (50%)			Step response
CD4		70% (30%)			Step response
CD5		100% (0%)		6493	Step response
CD6		30% (70%)			Step response
CD7		50% (50%)			Step response
CD8		70% (30%)			Step response
CD9 CD10		100% (0%)	50	0	Voltage sweep Step response
CD11 CD12		30% (70%)			Voltage sweep Step response
CD13 CD14		50% (50%)			Voltage sweep Step response
CD15 CD16		70% (30%)			Voltage sweep Step response
CD17 CD18		100% (0%)		8116	Voltage sweep Step response
CD19 CD20		30% (70%)			Voltage sweep Step response
CD21 CD22		50% (50%)			Voltage sweep Step response
CD23 CD24		70% (30%)			Voltage sweep Step response
CD25 CD26	C2H4	100% (0%)	40	0	Voltage sweep Step response
CD27 CD28		30% (70%)			Voltage sweep Step response
CD29 CD30		50% (50%)			Voltage sweep Step response
CD31 CD32		70% (30%)			Voltage sweep Step response
CD33 CD34		100% (0%)		6493	Voltage sweep Step response
CD35 CD36		30% (70%)			Voltage sweep Step response
CD37 CD38		50% (50%)			Voltage sweep Step response
CD39 CD40		70% (30%)			Voltage sweep Step response
CD25 CD26		100% (0%)	50	0	Voltage sweep Step response
CD27 CD28		30% (70%)			Voltage sweep Step response
CD29 CD30		50% (50%)			Voltage sweep Step response
CD31 CD32		70% (30%)			Voltage sweep Step response
CD33 CD34		100% (0%)		8116	Voltage sweep Step response
CD35 CD36		30% (70%)			Voltage sweep Step response
CD37 CD38		50% (50%)			Voltage sweep Step response
CD39 CD40		70% (30%)			Voltage sweep Step response

3.3. Flame Design

Two detailed test matrices are presented after respective summaries.

Spherical Flames: *These tests will emphasize measurements of three types of limits: sooting limits, radiative extinction limits, and kinetic extinction limits. Tests will involve normal convection direction only. A smaller number of tests will consider long-term burns to evaluate the possible existence of steady flames. These tests support Objectives A – C.*

Coflow Flames: *These tests will emphasize inverse coflow flames (highly desired), and flames with high oxygen concentrations in the oxidizer, which are not permitted in the CIR for spherical flames. Measurements will emphasize sooting limits, defined here as half-blue limits. A half-blue soot limit is a condition where the lowest visible yellow emissions are half way between the burner tip and the visible flame tip. Coflow tests will involve dynamic venting to maintain the set point pressure. These tests support Objectives A and C.*

Table 5.3.1

Test Matrix: Spherical Flame Tests
Burner: spherical
Tests are identified by S# (spherical), where # is the test point number. All tests are at 1 bar (or a setpoint pressure close to this) except Tests S68-107.

Test	Fluent X^1 (%)	Ambient X^2 (%)	Z_{st}	T_{ad} (K)	Comments
S1	C_2H_4/100	~O_2/21	0.064	2370	Use cabin air to do preliminary test of system operation, all diagnostics, and soot limit and extinction limits (see S6)
S2					Perform test of quasi-steady state flame.
S3					Increase fuel flow rate until radiative extinction. Reduce fuel flow rate to confirm extinction.
S4					Decrease fuel flow rate until kinetic extinction. Increase fuel flow rate to confirm extinction.
S5					Increase inert flow rate until soot-inception limit. Increase inert flow rate until extinction. Decrease inert flow rate to confirm extinction.
Evacuate and recharge chamber with O_2/50.					
S6	C_2H_4/100	O_2/50	0.135	2931	Identify soot-inception limit, with constant fuel and inert flow rates. Identify radiative extinction limit. Reignite and obtain kinetic extinction limit by reducing the total flow rate until extinction. Two flames will be observed.
S7	C_2H_4/5		0.757	1757	Soot limit and extinction limits (see S6)
S8	C_2H_4/10.8		0.590	2370	Soot limit and extinction limits (see S6)
Scrub and replenish to ~O_2/30 to obtain approximate results.					
S9	C_2H_4/100	~O_2/30	0.088	2649	Soot limit and extinction limits (see S6)
S10	C_2H_4/5		0.657	1595	Soot limit and extinction limits (see S6)
S11	C_2H_4/10		0.490	2070	Soot limit and extinction limits (see S6)
Evacuate and recharge chamber with O_2/30.					
S12	C_2H_4/100	O_2/30	0.088	2649	Soot limit and extinction limits (see S6)
S13	C_2H_4/5		0.657	1595	Soot limit and extinction limits (see S6)
S14	C_2H_4/10		0.490	2070	Soot limit and extinction limits (see S6)
Scrub and replenish to ~O_2/21 to obtain approximate results.					
S15	C_2H_4/100	~O_2/21	0.064	2370	Soot limit and extinction limits (see S6)
S16	C_2H_4/5		0.576	1454	Soot limit and extinction limits (see S6)
S17	C_2H_4/10		0.405	1837	Soot limit and extinction limits (see S6)
Evacuate and recharge chamber with O_2/21.					
S18	C_2H_4/100	O_2/21	0.064	2370	Soot limit and extinction limits (see S6)
S19	C_2H_4/5		0.576	1454	Soot limit and extinction limits (see S6)
S20	C_2H_4/10		0.405	1837	Soot limit and extinction limits (see S6)
Scrub and replenish to ~O_2/15 to obtain approximate results.					
S21	C_2H_4/100	~O_2/15	0.047	2012	Soot limit and extinction limits (see S6)
S22	C_2H_4/10		0.329	1595	Soot limit and extinction limits (see S6)
S23	C_2H_4/20		0.197	1803	Soot limit and extinction limits (see S6)
Evacuate and recharge chamber with O_2/15.					
S24	C_2H_4/100	O_2/15	0.047	2012	Soot limit and extinction limits (see S6)
S25	C_2H_4/10		0.329	1595	Soot limit and extinction limits (see S6)
S26	C_2H_4/20		0.197	1803	Soot limit and extinction limits (see S6)
Evacuate and recharge chamber with O_2/50.					
S27	C_2H_4/20	O_2/50	0.438	2649	Soot limit and extinction limits (see S6)

S28	C_2H_4/40		0.280	2820	Soot limit and extinction limits (see S6)
S29	C_2H_4/60		0.206	2882	Soot limit and extinction limits (see S6)
Scrub and replenish to ~O_2/30 to obtain approximate results.					
S30	C_2H_4/19	~O_2/30	0.336	2370	Soot limit and extinction limits (see S6)
S31	C_2H_4/40		0.194	2552	Soot limit and extinction limits (see S6)
S32	C_2H_4/60		0.138	2606	Soot limit and extinction limits (see S6)
Evacuate and recharge chamber with O_2/30.					
S33	C_2H_4/19	O_2/30	0.336	2370	Soot limit and extinction limits (see S6)
S34	C_2H_4/40		0.194	2552	Soot limit and extinction limits (see S6)
S35	C_2H_4/60		0.138	2606	Soot limit and extinction limits (see S6)
Scrub and replenish to ~O_2/21 to obtain approximate results.					
S36	C_2H_4/20	~O_2/21	0.254	2113	Soot limit and extinction limits (see S6)
S37	C_2H_4/40		0.145	2271	Soot limit and extinction limits (see S6)
S38	C_2H_4/60		0.102	2326	Soot limit and extinction limits (see S6)
Evacuate and recharge chamber with O_2/21.					
S39	C_2H_4/20	O_2/21	0.254	2113	Soot limit and extinction limits (see S6)
S40	C_2H_4/40		0.145	2271	Soot limit and extinction limits (see S6)
S41	C_2H_4/60		0.102	2326	Soot limit and extinction limits (see S6)
Scrub and replenish to ~O_2/15 to obtain approximate results.					
S42	C_2H_4/20	~O_2/15	0.197	1803	Soot limit and extinction limits (see S6)
S43	C_2H_4/40		0.109	1929	Soot limit and extinction limits (see S6)
S44	C_2H_4/50		0.089	1956	Soot limit and extinction limits (see S6)
Evacuate and recharge chamber with O_2/15.					
S45	C_2H_4/20	O_2/15	0.197	1803	Soot limit and extinction limits (see S6)
S46	C_2H_4/40		0.109	1929	Soot limit and extinction limits (see S6)
S47	C_2H_4/50		0.089	1956	Soot limit and extinction limits (see S6)
This completes the required tests. All subsequent tests are highly desired or desired.					
S48 to S67	C_2H_4/5 to C_2H_4/100	O_2 and CO_2			Highly desired: perform subset of tests S6-47 with CO_2 as both fluent and ambient inert (circa 20 test points). Desired: scrub to remove H_2O, not CO_2.
S68 to S87	C_2H_4/5 to C_2H_4/100	O_2/15 to O2/50			Highly desired: perform subset of tests S6-47 at 0.2 bar (circa 20 test points).
S88 to S107	C_2H_4/5 to C_2H_4/100	O_2/15 to O2/50			Highly desired: perform subset of tests S6-47 at 0.5 bar (circa 20 test points).
S108 to S127	CH_4/5 to CH_4/100	O_2/15 to O2/50			Desired: perform subset of tests S6-47 with CH_4 as fuel (circa 20 test points).

[1]Balance is N2, except tests S48-89. Fluent flowrates will be selected such that the C2H4 (or CH4) mass flow rate is 1.5 mg/s or a setpoint close to this (except tests S3-4 and tests for kinetic extinction). For tests where the mole fraction is varied, the listed mole fraction is an estimate of the starting condition.
[2]Assuming scrubbing capability, the CO2 and H2O will be scrubbed after some runs and reactants replenished as needed. Different O2 mole fractions (up to 50%) for chamber fills may be specified during uplink.

Table 5.3.2

Test Matrix: Coflow Flame Tests

Burner: coflow

Tests are identified by IC# (inverse coflow) or NC# (normal coflow), where # is the test point number. All tests are at 1 bar except as noted, with dynamic venting. Fuel mole fraction will vary for all tests; the listed fuel mole fraction is TBD for the starting condition. The coflow tests are highly desired or desired.

Test	**Inner Jet *X*[1] (%)**	**Outer Jet *X*[2] (%)**	***Zst***	***Tad (K)***	**Comments[3]**
Tests IC1-17 involve the coflow burner in inverse mode. Tests IC1-9 are highly desired. Tests IC10-17 are desired. Evacuate and recharge chamber with N2.					
IC1	O2/85	C2H4/9	0.738	2370	With central jet at ~0.2 lpm, coflow at ~2 lpm, examine effects of flow rate and residence time. Vary fuel concentration to identify soot-inception (half-blue) limit.
IC2	O2/50	C2H4/11	0.586	2370	Identify half-blue soot limit (see IC1).
IC3	O2/30	C2H4/19	0.336	2370	Identify half-blue soot limit (see IC1).
IC4	O2/85	C2H4/9	0.738	2370	Perform test IC1 at 0.2 bar.
IC5	O2/50	C2H4/11	0.586	2370	Perform test IC2 at 0.2 bar.
IC6	O2/30	C2H4/19	0.336	2370	Perform test IC3 at 0.2 bar.
IC7	O2/85	C2H4/9	0.738	2370	Perform test IC1at 0.5 bar.
IC8	O2/50	C2H4/11	0.586	2370	Perform test IC2 at 0.5 bar.
IC9	O2/30	C2H4/19	0.336	2370	Perform test IC3 at 0.5 bar.
IC10	O2/85	C2H4/9	0.738	2370	Perform test IC1 at 2 bar.
IC11	O2/50	C2H4/11	0.586	2370	Perform test IC1 at 2 bar.
IC12	O2/30	C2H4/19	0.336	2370	Perform test IC2 at 2 bar.
IC13	O2/85	C2H4/9	0.738	2370	Perform test IC1 with CO2 as fuel inert and N2 as oxidizer inert
IC14	O2/50	C2H4/11	0.586	2370	Perform test IC2 with CO2 as fuel inert and N2 as oxidizer inert
IC15	O2/30	C2H4/19	0.336	2370	Perform test IC3 with CO2 as fuel inert and N2 as oxidizer inert
IC16	O2/85	CH4/9	0.738	2370	Perform test IC1 with CH4 as fuel.
IC17	O2/50	CH4/11	0.586	2370	Perform test IC2 with CH4 as fuel.
IC18	O2/30	CH4/19	0.336	2370	Perform test IC3 with CH4 as fuel.
Tests NC1-17 involve the coflow burner in normal mode. These tests are desired. Evacuate and recharge chamber with N2.					
NC1	C2H4/9	O2/85	0.738	2370	Identify half-blue soot limit (see IC1).
NC2	C2H4/11	O2/50	0.586	2370	Identify half-blue soot limit (see IC1).
NC3	C2H4/19	O2/30	0.336	2370	Identify half-blue soot limit (see IC1).
NC4	C2H4/9	O2/85	0.738	2370	Perform test NC1 at 0.2 bar.
NC5	C2H4/11	O2/50	0.586	2370	Perform test NC2 at 0.2 bar.
NC6	C2H4/19	O2/30	0.336	2370	Perform test NC3 at 0.2 bar.
NC7	C2H4/9	O2/85	0.738	2370	Perform test NC1at 0.5 bar.
NC8	C2H4/11	O2/50	0.586	2370	Perform test NC2 at 0.5 bar.
NC9	C2H4/19	O2/30	0.336	2370	Perform test NC3 at 0.5 bar.
NC10	C2H4/9	O2/85	0.738	2370	Perform test NC1 at 2 bar.
NC11	C2H4/11	O2/50	0.586	2370	Perform test NC1 at 2 bar.
NC12	C2H4/19	O2/30	0.336	2370	Perform test NC2 at 2 bar.
NC13	C2H4/9	O2/85	0.738	2370	Perform test NC1 with CO2 as fuel inert and N2 as oxidizer inert
NC14	C2H4/11	O2/50	0.586	2370	Perform test NC2 with CO2 as fuel inert and N2 as oxidizer inert

NC15	C2H4/19	O2/30	0.336	2370	Perform test NC3 with CO2 as fuel inert and N2 as oxidizer inert
NC16	CH4/9	O2/85	0.738	2370	Perform test NC1 with CH4 as fuel.
NC17	CH4/11	O2/50	0.586	2370	Perform test NC2 with CH4 as fuel.
NC18	CH4/19	O2/30	0.336	2370	Perform test NC3 with CH4 as fuel.

[1]Inner jet flowrate will be selected such that the C2H4 (or CH4) mass flow rate is 1.5 mg/s.
[2]Each test point does not imply a fresh chamber fill with N2. Assuming scrubbing capability of the CIR, the CO2 and H2O will be scrubbed after previous run and reactants replenished as needed for next test.
[3]Measurements include temperature, soot volume fraction, and color video unless otherwise specified. Continuously record the soot volume fraction. Download on demand. A half-blue soot limit is a condition where the lowest visible yellow emissions are half way between the burner tip and the visible flame tip.

3.4. s-Flame

The three-part test matrix below is designed to meet the complete success criteria, addressing all scientific objectives listed above.

*All experimental sets will address transient phenomenon, as the flame evolves from localized ignition towards "steady" behavior, corresponding to Objective (**A**). The flames evolve in a quasi-steady state manner (becoming history independent), after a short initial transient.*

*The rationale for this test matrix is to utilize various mixtures to assess both chemical and transport effects (including radiative) on flame behavior. Pure H_2 and pure CH_4 are utilized to assess kinetic mechanisms associated with each. Additionally, pure H_2 only produces H_2O as its radiative product, thereby isolating its radiative properties. Mixtures composed of both H_2 and CH_4 are used to examine their combined chemical and transport effects. Various inerts which affect characteristic flame temperature and transport (molecular and radiative), all in the same mole fractions, are utilized for comparison. C_2H_4 allows for the examination of a fuel with nominal unity Le number. Additionally, its characteristic sooting nature directly addresses our basic science objectives focusing on (**A**) spreading of flame sheets, (**B**) dual extinction states, and (**C**) flamefront instabilities.*

The fuel/inert mixtures in the REQUIRED experiment sets 1-2 include H_2/CH_4 mixtures (see subsets a, b, c) and H_2 and CH_4 as pure fuels (see subsets d, e) aimed at addressing chemical kinetic aspects. The inert mole fractions are all fixed at 55% for baseline comparison. As can be seen, the difference between sets 1 and 2 is the inert (N_2 versus He), which is chosen to assess transport (e.g. diffusive properties) effects on flame stability. For example, experimental set 2 is aimed at inducing the pulsating instability for Le > 1, corresponding to Objective ©. The fuel components and their relative compositions are the same for sets 1-2, with different inert species in balance; similarly, the ambient composition reflects the use of a different inert species in the fuel mixture. It is noted that the characteristic flame temperatures (which will affect the Zeldovich number, Ze) will be different for the two experimental sets affecting stability and extinction.

*Experiment sets 1-2 will also assess radiative extinction for high flow rates (see i, ii, iii under the flow rate category) and kinetic extinction for low flow rates (see iv and v under the flow rate category), corresponding to Objective (**B**). With regard to radiative extinction, mixture compositions of 25%H_2/20%CH_4, 20%H_2/25%CH_4, and 30%H_2/15%CH_4 have been shown in drop-tower experiments to be characterized by* *different radiative extinction times. These mixtures also eschew sooty ignition (due to strong H_2 presence), which can otherwise result in asymmetrically trapped soot that deteriorates flame sphericity. With respect to kinetic extinction, note that a step change from a higher flow rate to a lower one is needed because starting with a flow rate below the extinction limit would preclude flame establishment in the first place.*

*The HIGHLY DESIRED experiment sets 3-4 utilize C_2H_4 as fuel. With a nominal Le of unity with respect to air for this fuel, a baseline case (experiment set 3) for flame stretch and thermaldiffusive stability effects is established. The fuel and inert mole fractions for the C_2H_4/inert are varied to address different fuel concentration effects on sooting, which can impact Objectives (**A**) flame spread behavior, (**B**) extinction, and (**C**) flame stability. Soot will also enhance flame radiation. Since characteristic residence times will affect sooting tendencies, two flow rates are investigated for each mixture. Experiment set 4 replaces the inert, N_2, of set 3 with He, to better isolate Le>1 instabilities, corresponding to Objective (**C**), as well as examine extinction for characteristically higher flame temperatures.*

*The DESIRED experiment sets 5-6 examine the same fuel mixtures of the REQUIRED and HIGHLY DESIRED experiment sets, but with CO_2 as inert, including that for the ambient. N_2 and He are radiatively transparent gases; while CO_2 is an optically participating gas. While use of CO_2 should result in a characteristically lower flame temperature, the highly reabsorptive CO_2 species can minimize net radiative heat loss affecting flame dynamics and extinction. Objectives (**A**)-(**C**) are addressed by these experiments.*

The maximum duration of any test is **25**s.

Table 5.4.1

Test Matrix: Required Burner: spherical					
Exp Set	**Sub set**	**Fuel Mixture**	**Ambient**	**Flow rate (cc/s)**	**No. of runs**
1	(a)	25%H2/20%CH4/55%**N2**	21%O2/ 79%**N2**	(i) 5 (entire duration, 25s) (ii) 10 (entire duration, 25s) (iii) 15 (entire duration, 25s) (iv) 10 (5s)→2 (rest of duration) (v) 5 (5s) →2 (rest of duration)	5
	(b)	20%H2/25%CH4/55%**N2**		(i) through (v) as shown above	5
	(c)	30%H2/15%CH4/55%**N2**		(i) through (v) as shown above	5
	(d)	45%H2/55%**N2**		(x) 1 (entire duration, 25s) (y) 2 (entire duration, 25s) (z) 2 (5s) →0.5 (rest of duration)	3
	(e)	45%CH4/55%**N2**		(i) through (v) as shown in (a)	5
2	(a)	25%H_2/20%CH_4/55%**He**	21%O_2/ 79%**He**	(i) 5 (entire duration, 25s) (ii) 10 (entire duration, 25s) (iii) 15 (entire duration, 25s) (iv) 10 (5s) →2 (rest of duration) (v) 5 (5s) →2 (rest of duration)	5
	(b)	20%H_2/25%CH_4/55%**He**		(i) through (v) as shown above	5
	(c)	30%H_2/15%CH_4/55%**He**		(i) through (v) as shown above	5
	(d)	45%H_2/55%**He**		(x) 1 (entire duration, 25s) (y) 2 (entire duration, 25s) (z) 2 (5s) →0.5 (rest of duration)	3
	(e)	45%CH_4/55%**He**		(i) through (v) as shown in (a)	5
					46 total

Table 5.4.2

Test Matrix: Highly Desired Burner: spherical					
Exp Set	**Sub set**	**Fuel Mixture**	**Ambient**	**Flow rate (cc/s)**	**No. of runs**
3	(a)	20%C_2H_4/80%**N_2**	21%O2/ 79%**N2**	(i) 5 (entire duration, 25s) (ii) 10 (entire duration, 25s)	2
	(b)	25%C_2H_4/75%**N_2**		(i) and (ii) as shown above	2
	(c)	30%C_2H_4/70%**N_2**		(i) and (ii) as shown above	2
4	(a)	20%C_2H_4/80%**He**	21%O_2/ 79%**He**	(i) 5 (entire duration, 25s) (ii) 10 (entire duration, 25s)	2
	(b)	25%C_2H_4/75%**He**		(i) and (ii) as shown above	2
	(c)	30%C_2H_4/70%**He**		(i) and (ii) as shown above	2
					12 total

Table 5.4.3

Test Matrix: Desired Burner: spherical					
Exp Set	**Sub set**	**Fuel Mixture**	**Ambient**	**Flow rate (cc/s)**	**No. of runs**
5	(a)	25%H_2/20%CH_4/55%$\mathbf{CO_2}$	21%O_2/ 79%$\mathbf{CO_2}$	(i) 5 (entire duration, 25s) (ii) 10 (entire duration, 25s) (iii) 15 (entire duration, 25s) (iv) 10 (5s) →2 (rest of duration) (v) 5 (5s) →2 (rest of duration)	5
	(b)	20%H_2/25%CH_4/55%$\mathbf{CO_2}$		(i) through (v) as shown above	5
	(c)	30%H_2/15%CH_4/55%$\mathbf{CO_2}$		(i) through (v) as shown above	5
	(d)	45%H_2/55%$\mathbf{CO_2}$		(x) 1 (entire duration, 25s) (y) 2 (entire duration, 25s) (z) 2 (5s) →0.5 (rest of duration)	3
	(e)	45%CH_4/55%$\mathbf{CO_2}$		(i) through (v) as shown in (a)	5
6	(a)	20%C_2H_4/80%$\mathbf{CO_2}$	21%O_2/ 79%$\mathbf{CO_2}$	(i) 5 (entire duration, 25s) (ii) 10 (entire duration, 25s)	2
	(b)	25%C_2H_4/75%$\mathbf{CO_2}$		(i) and (ii) as shown above	2
	(c)	30%C_2H_4/70%$\mathbf{CO_2}$		(i) and (ii) as shown above	2
					29 total

4. Success Criteria

4.1. CLD Flame

Success of the Coflow Laminar Diffusion Flame experiment will be judged on meeting the stated experimental objectives by acquiring results that lead to the stated data end products. Three different levels of success – minimal, significant, and complete success – are defined. An additional level of success is defined as satisfying our overall project goals, which is not required for complete experimental success.

4.1.1. Minimal Success

Minimal success is defined to mean acquisition of sufficient scientific data from the experiment to perform a direct comparison with the numerical computations and publish at least one journal article. This minimal level of success may be achieved by obtaining basic information about the flame characteristics from the color images or UV images, possibly for a subset of the flame conditions outlined above. Meaningful subsets of the data might include data from a single fuel (methane or ethylene, but not both) or from either weak or sooting flames, but not both. Data would remain valuable for comparisons with computational models, albeit not as complete as would be desirable. For example, minimal success might come from obtaining data as follows:

1. Color images of nonsooting flames only (SDEP A1).
2. UV images of *OH** (and *CH**, desired) luminosity from nonsooting flames (towards SDEP A2).

This would provide data that would allow us to determine several of our science data end products including the following:

- Observation of lift-off heights as a function of dilution level (SDEP A4).
- Observation of extinction limits as a function of dilution level (SDEP A6).
- Observation of flame shape and size (SDEP A5).
- 2D images of *OH** (and *CH**, desired) concentrations (SDEP A2).
- Peak concentrations of *OH** (and *CH**, desired) as a function of fuel dilution (SDEP A3).

Similar “minimal success” subsets of data could be defined for sooting flames only, or datasets from one fuel only. In any of these cases, a paper could still be published on the limited results and their comparison to the computations.

4.1.2. Significant Success

Significant success is defined to mean acquisition of sufficient scientific data from the experiment to perform a direct comparison with the numerical computations and publish several journal articles. In addition to the information obtained for a minimal level of success, a significant level of success may be achieved by obtaining more detailed information about the flame characteristics from UV images for species concentrations and from soot diagnostics for soot volume fraction (for example):

1. 2D images of soot laser extinction and associated reference images
2. 2D images of multi-color soot luminosity (from pyrometry data).

This would provide data that would allow us to determine several of our science data end products including the following:

- 2D images of soot volume fraction (SDEP B11).
- 2D images of soot temperatures (SDEP B9).

4.1.3. Complete Success

Complete success is defined to mean acquisition of all data related to the experimental objectives. In addition to the information obtained for a significant level of success, a complete level of success may be achieved by obtaining complete information about the flame characteristics using the available diagnostic techniques, including full information on temperatures, extinction and sooting tendencies across the full range of flow conditions:

1. Multi-color images of TFP data, including reference images.
2. Images of soot extinction representing the peak soot volume fraction, including reference images.
3. Soot luminosity images representing the peak soot temperature, including reference images.

This would provide data that would allow us to determine several of our science data end products including the following:

- Radial temperature profiles from TFP (SDEP A7 and B8).
- Combined temperature fields from soot pyrometry and TFP (SDEP A7 and B8 with B9).
- Peak soot volume fraction as a function of fuel dilution over the full range of flow velocities (SDEP B12).
- Peak temperature as a function of fuel dilution over the full range of flow velocities (SDEP A8 and B10).

4.2. E-FIELD Flames

4.2.1. Minimal Success

- Obtain V-I curve in quasi-steady conditions for undiluted methane fuel on either diameter of the gas jet burner or the co-flow burner
- Simultaneously capture color images of flame responding to electric field during V-I sweep

4.2.2. Complete Success

All of the above plus:
- Obtain V-I curve in quasi-steady conditions for both fuels (methane and ethylene) on one gas jet burner and the co-flow burner with a range of inert dilution of fuel
- Simultaneously capture flame images during voltage sweeps to allow measurement of liftoff height has a function of applied voltage
- Measure soot luminosity (radiometer measurement) as a function of applied voltage during VI sweeps and step changes

4.2.3. Superior Success

All of the above plus:
- Demonstrate open loop control of flame near sooting and stability limits using ion current and luminosity as sensors by determining the decrease (or increase) in soot luminosity and by evaluating the extent to which stability limits can be extended using an electric field
- (Desired) Obtain thermal field information for the gas jet or coflow flame to visualize ion driven wind

4.3. Flame Design

The success of the proposed experiment will be judged vis-à-vis the stated objectives. The requirements for four levels of success are stated.

4.3.1. Minimal Success

Minimal success requires:
- Obtain color images of a spherical flame of C_2H_4 flowing into diluted oxygen that passes its sooting limit, passes its radiative extinction limit, and has a total burn time that exceeds 20 s.
- Obtain color images of a spherical flame of C_2H_4 flowing into air as a function of *m*.

4.3.2. Substantial Success

Substantial success additionally requires:
- Measure peak temperature as a function of *m* for a spherical flame of C_2H_4 flowing into diluted oxygen at quasi-steady conditions.
- Obtain soot inception limits and extinction limits for spherical C_2H_4 flames as functions of Z_{st} and T_{ad}.

4.3.3. Complete Success

Complete success (which requires completion of the required test matrix) additionally requires:
- Perform tests S1 – 47 or a similar set of spherical flame tests.
- Obtain temperature distributions at (or near) the sooting and extinction limits of spherical flames.

- Measure soot volume fraction profiles for spherical diffusion flames at low and high Z_{st}.

4.3.4. Superior Success

Superior success (which includes only desired items) additionally requires:
- Obtain color images of inverse coflow flames of diluted oxygen flowing into C_2H_4 at quasi-steady conditions as a function of *m*.
- Obtain soot inception limits and extinction limits for inverse coflow flames of diluted oxygen flowing into C_2H_4 as functions of Z_{st} and T_{ad}.
- Obtain soot inception limits and extinction limits with CO_2 diluent as functions of Z_{st} and T_{ad} for normal spherical and (coflow) inverse flames.
- Obtain soot inception limits and extinction limits for C_2H_4 as functions of Z_{st} and T_{ad} for normal and (coflow) inverse flames at pressures of 0.2 and 0.5 atm.
- Obtain soot inception limits and extinction limits for CH_4 as functions of Z_{st} and T_{ad} for normal spherical and (coflow) inverse flames.

4.4. s-Flame

Success of the s-Flame Experiment will be judged on meeting the stated science objectives. Three different levels, minimal, substantial, and complete success, are defined below.

4.4.1. Minimal Success

Minimal success is defined to mean sufficient scientific data return from the experiment to perform a direct comparison with the numerical flame simulation and publish a single archival journal article. This minimal level of success may be achieved by obtaining (for example):

1. Observations of transient flame phenomena leading toward steady state flames for 1 CH_4 case and 1 C_2H_4 case. Such observations must include, at a minimum, the flow and boundary condition measurements, flame temperature data and image sequences from at least two orthogonal imaging systems; or
2. Observations of flame extinction at both low and high system Damkohler number for 1 case. Such observations must include, at a minimum, the flow and boundary condition measurements, flame temperature data and image sequences from at least two orthogonal imaging systems; or
3. Observations of spherical soot formation in 1 C_2H_4 case. Such observations must include, at a minimum, the flow and boundary condition measurements, flame temperature data and image sequences from at least two orthogonal imaging systems.

4.4.2. Significant Success

Significant Success is defined to mean sufficient scientific data return from the experiment to perform direct comparison with the numerical flame simulation resulting in multiple archival journal publications, but less return that defined for complete success. This significant level of success may be achieved by obtaining (for example):

1. Observations of at least two instances of flame front instabilities including at least one hydrocarbon fuel. Such observations must include, at a minimum, the flow and boundary condition measurements, and data quantifying the flame front

oscillations from image sequences from at least two of the three imaging systems and from the radiometer instrument; or

2. Combinations or extensions (in terms of number of mixture ratios for a single hydrocarbon fuel or number of hydrocarbon fuels) of at least two of items 1 through 4 defined for minimum success.

4.4.3. Complete Success

Complete Success is defined as meeting all of the experiment objectives, including as a minimum:

1. Observations of transient flame phenomena leading toward steady state flames for at least three different mixture ratios of each of two hydrocarbon fuels and two diluents. Such observations must include, at a minimum, the flow and boundary condition measurements, flame temperature data, image sequences from two orthogonal imaging systems, and radiometer data; and
2. Observations of flame extinction at both low and high system Damkohler number for at least three different mixture ratios of each of two hydrocarbon fuels and two diluents. Such observations must include, at a minimum, the flow and boundary condition measurements, flame temperature data, image sequences from two orthogonal imaging systems, and radiometer data; and
3. Observations of at least two instances of flame front instabilities each including at least one hydrocarbon fuel. Such observations must include, at a minimum, the flow and boundary condition measurements, and data quantifying the flame front oscillations from image sequences from at least two orthogonal imaging systems and from the radiometer instrument; and
4. Observations of soot formation. Such observations must include the flow and boundary condition measurements, flame temperature data, image sequences from all imaging systems, temperature data, and radiometer data.

APPENDICES

There are no requirements in the appendices; they are only provided for reference.

A: Spherical Burner Design Reference
B: Gas-Jet Burner Design Reference
C: Coflow Burner Design Reference
D: Electric Field Design Reference
E: Gas Delivery Design Concept

Appendix A: Spherical Burner Design Reference

Both the s-Flame and Flame Design research teams have significant experience with the manufacture of porous spherical burners from sintered metal. Both have relied upon an approach of fabricating the burners in lots and then testing them to identify the ones that best produce flames which are spherical and concentric with the burner. Given buoyancy's role, this verification testing has been conducted in the 2.2s Drop Tower or in normal gravity under conditions where buoyant effects have been reduced (but not eliminated).

s-Flame

The s-Flame burners are described in general terms here, but note that a proprietary process was used for manufacturing the small burners.

Sphere design: *Sintered porous metal apparently works best, rather than porous ceramic or hollow spheres with holes created by EDM. The spheres are "solid" with sintered grains except where the feed tube inserts. This was done by incorporating a feed tube during pressing/heating of the mold. This "tunnel" was then tapped for the feed tube to be screwed into. The depth at which the feed tube is inserted into the 'tunnel' is a key parameter, as there is a small volume, or open cavity, at the 'center' of the burner, that affects flow uniformity. The depth of the feed tube penetration was optimized via modeling with CFD. If it is possible to press the mold uniformly (radially), rather than in 2 hemispheres (as done by the company), that should work best.*

Sphere material: *- sintered bronze (and possibly other materials)*

Sphere sizes: *at least 1/8" to ½" in diameter. Commercially, >1/2" diameters work best. Smaller sizes need to be manufactured at Princeton to work well.*

Sphere manufacturer: *Custom-fabricated spheres from Princeton are believed to give the best results. GKN Sintered Metals has manufactured the spheres with a provided spec and protocol.*

Tube diameter: *These sizes of the feed tubes depended on the burner sizes. For the 1/4" and 1/2" diameter porous burners, the tubing used are 0.025" O.D./0.017" I.D. and 0.058" O.D./0.042" I.D., respectively.*

Tube attachment: *The feed tubes are threaded, and the spheres are tapped, to establish the supply connection. There is no sealant used for the threaded joints. Since the tube is inserted almost to the center, s-Flame rarely has leaking effects.*

Burner verification: *Flame shape for inverse diffusion flames in a micro-buoyancy chamber is the standard test for s-Flame. There is a big difference between diffusion flames and premixed flames, as the issuing velocity is at least an order of magnitude less for the diffusion flames.*

Successful fabrication: *For the commercial spheres, perhaps 30% are acceptable. Sometimes, only 1 in 10 work out.*

Thermocouple attachment: *The s-Flame researchers measure the burner surface temperature using a K type thermocouple which is simply tied to the feed tube with the junction contacting the base of the sphere.*

Flame Design

The Flame Design team currently has two spherical burners, described below, which meet their requirements for flame shape.

Burner numbers: *8 and 11*
Sphere manufacturer: *Chand Associates, Worcester, MA, 508-791-9549 (see below)*
Sphere and tube material: *stainless steel*
Sphere pore size: *10 micron, sintered*
Sphere outside diameter: *6.35 mm (0.25 inch)*
Sphere hole diameter (to center): *1.59 mm (1/16 inch)*
Tube diameter: *1.59 mm (1/16 inch)*
Tube attachment method: *epoxy*
Tubes epoxied by: *Chip Redding (#8) and John Napier (#11), NASA Glenn*

The porous spheres manufactured for Flame Design are not available as a standard product as described in the e-mail below.

From: Sales [mailto:sales@chandeisenmann.com]
Sent: Tuesday, October 21, 2008 6:41 PM
To: Stocker, Dennis P. (GRC-REC0)
Subject: Porous Spheres?

Good Afternoon Dennis;

Thank you for inquiring about the porous sintered metal products that we manufacture. We do not make spherical parts as a regular production item. However, many years ago, we designed one special pressing tool to make a pilot run of 0.250" OD spherical parts for NASA Glenn.

We could make try to make porous parts, but this would be a development project.

Sincerely,

Mark Eisenmann

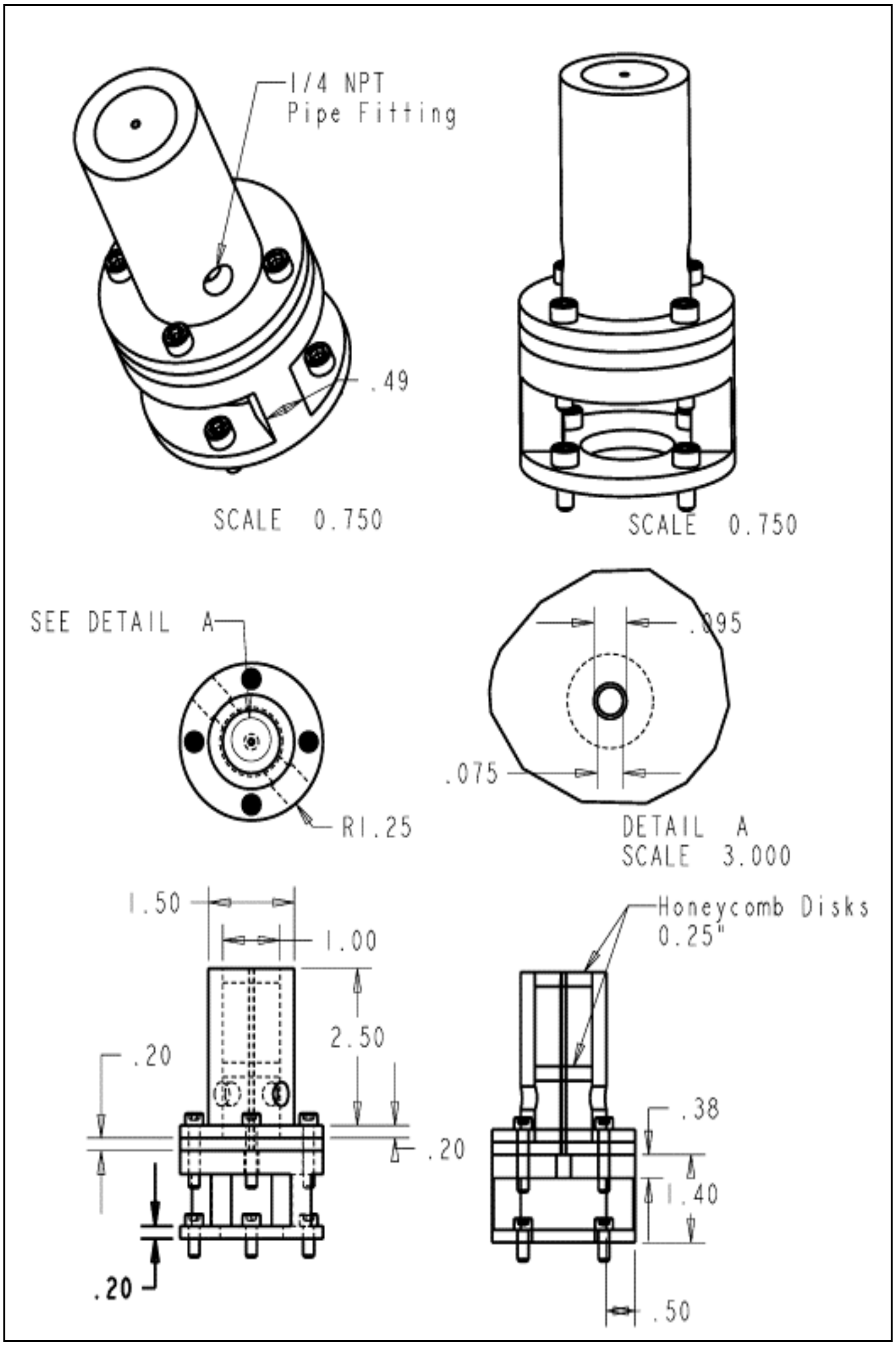
Chand Eisenmann Metallurgical
258 Spielman Highway
Burlington, CT 06013 USA

Telephone: 860-675-5000
Fax: 860-675-0521
Email: me@chandeisenmann.com
Website: www.chandeisenmann.com

Appendix B: Gas-Jet Burner Design Reference

Currently blank.

Appendix C: Coflow Burner Design Reference



Figures 2 and 3. *Schematic and photo of a burner developed by the PI team for CLD Flame for their ground-based experiments. The depicted schematic incorporates a suggested revision to minimize the volume of the fuel between the flow controller and the burner exit. Dimensions are in inches. Note the use of the honeycomb to create a plug flow (i.e., flat velocity profile) for the coflow. The central fuel tube has a length/diameter ratio of roughly 40 in order to develop a parabolic flow profile. The normal-gravity flames produced by this burner are typically less than 2.5 cm tall, with a maximum 1g diameter of about 0.6 cm.*

Appendix D: Electric Field Design Reference

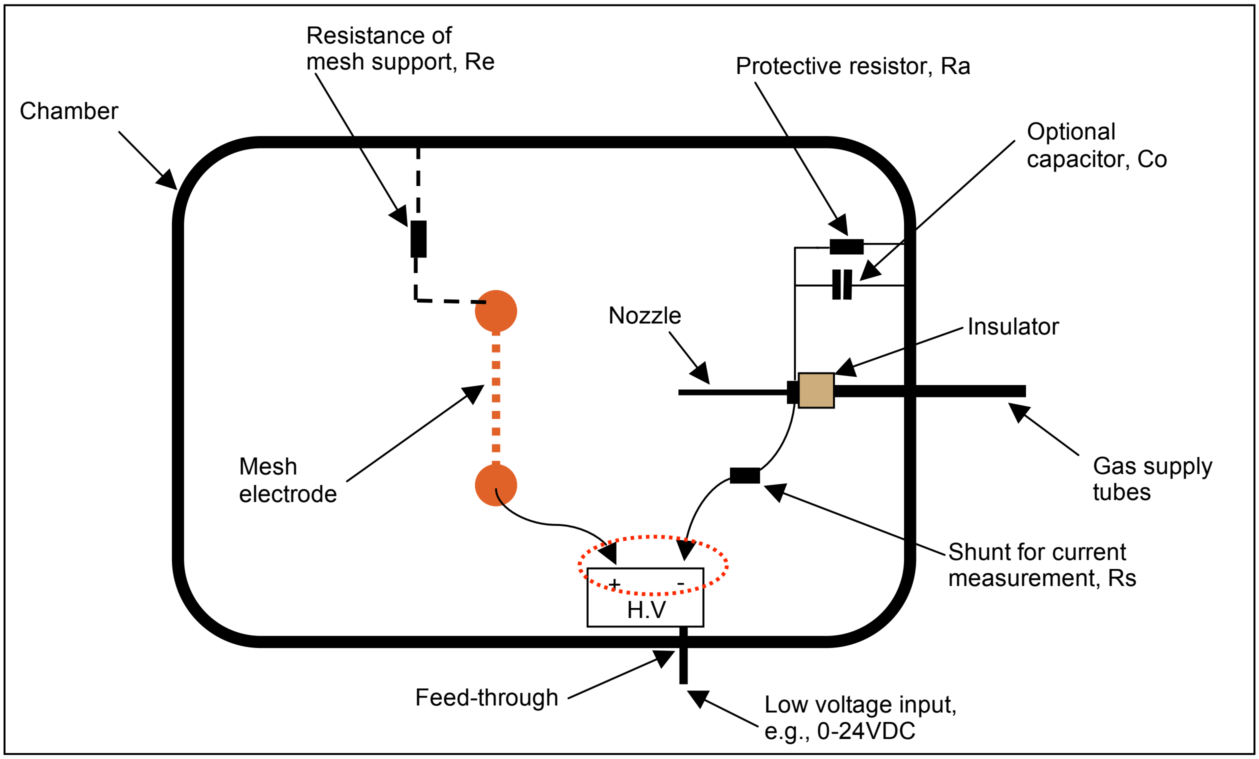


Figure 4. *Electric field schematic.*

The protective resistor, Ra, is needed to keep the nozzle and the chamber at the same potential, without connecting them directly. If the electrode mesh accidentally touches the chamber, the current in the high voltage (H.V.) loop can be limited by the protective resistor. In normal operation, the protective resistor (Ra) can keep the chamber and the burner (nozzle) at the same potential. A value of 10 mega-ohms is suggested for the resistor, based on 1 mA current at 10 kV. Although the resistor would be large, a 15 watt rating is suggested based on the product of 10 kV and 1 mA, with a 1.5 safety factor. But it is very conservative to assume a steady state current, so a smaller wattage such as 1 watt could be used. In that case, if the short circuit is momentary, the resistor will survive. If it is a long duration event, the resistor will fail, but that will prevent further damage like a fuse for the high voltage circuit. The capacitor, Co, is recommended as it would allow for passage of a transient. A capacitor of 0.01MFD and 1.5kV is recommended, which should be of the size close to an AAA battery.

The effective resistance of the insulator between the burner and the chamber (and gas supply tubes) should be much greater than that of the protective resistor, Ra. As such, a resistance of 100 mega-ohms is suggested.

An effective resistance of 200 giga-ohms is recommended for the insulation between the mesh electrode and the chamber. With that resistance, leaking current at 10 kV would be 0.05 mA, which is sufficiently small in comparison with estimated flame current of ~ 1 mA.

Appendix E: Flow Control Design Concept

Gas delivery and flow control by the CIR's Fuel/Oxidizer Management Assembly (FOMA) is insufficient for most (if not all) of the ACME tests. A major reason is that the FOMA does not provide means for mixing an inert with the fuel to vary its concentration. Furthermore, the default Mass Flow Controllers (MFCs) that will launch as part of the FOMA have been selected for their ability to provide high flow rates. As a result, these MFCs are very inaccurate at low flow rates (because of their uncertainty of ±1% of full scale flow). The resulting uncertainty is especially critical when blending gases and testing at or near instability, extinction, or soot inception limits.

The ACME tests can be accommodated with the FOMA with the inclusion of an additional pair of MFCs on the ACME insert, where each of those MFCs can be exchanged for another with a different flow range.

An example list of ACME MFCs follows, which may not be complete and where the listed flows are on a nitrogen basis. The current list of 10 MFCs amounts to only ~3 MFCs per experiment, and many are used by multiple experiments.

Fuel/Inert (F/I)	***Oxidizer/Inert (O/I)***
0.02 slpm, qty=1 [1,4]	*0.02 slpm, qty=1* [1]
0.1 slpm, qty=1 [1,2]	*0.05 slpm, qty=1* [2,4]
0.2 slpm, qty=1 [1,3]	*0.1 slpm, qty=1* [1]
0.5 slpm, qty=1 [3,4]	*2 slpm, qty=1* [3,4]
	5 slpm, qty=1 [3]
	15 slpm, qty=1 [3]

The need for ACME specific MFCs could be reduced, but not eliminated, by having exchangeable FOMA MFCs with appropriate flow ranges. The need for MFCs could also be reduced by limiting the variety of flow ranges, which would also reduce crew operations but significantly increase uncertainty in flow measurement and control. The example list above was specified to (1) minimize MFC changes during a specific experiment and (2) yield flow uncertainties that should generally be no greater than ±10% (of the actual flow) when accounting for a full scale uncertainty of ±1% in the MFCs. In this regard, note that it is desired that the flow uncertainty be less than ±1% of actual flow.

The following pages describe and illustrate flow control approaches to accommodate 5 different ACME test configurations. Of those 5 configurations, the last 3 described are only applicable to the desired coflow testing in the Flame Design experiment. Based on the current Flame Design test matrix, configurations B2 and C2 are not required for any of the experiments.

(A) Spherical and Gas-Jet Burner Tests

Fuel

FOMA fuel bottle at GB2
FOMA MFC1 (2 slpm) typically driven full open for ACME control
QD11 at the chamber's interface resource ring
ACME MFC (e.g., 0.5 slpm) ***or*** *no ACME MFC (for FOMA flow control)*
burner mixing plenum

Nitrogen (inert)

N2 supply or FOMA inert bottle at GB7
branch with no flow control
QD12 at the chamber's interface resource ring
ACME MFC (e.g., 1 slpm)
burner mixing plenum

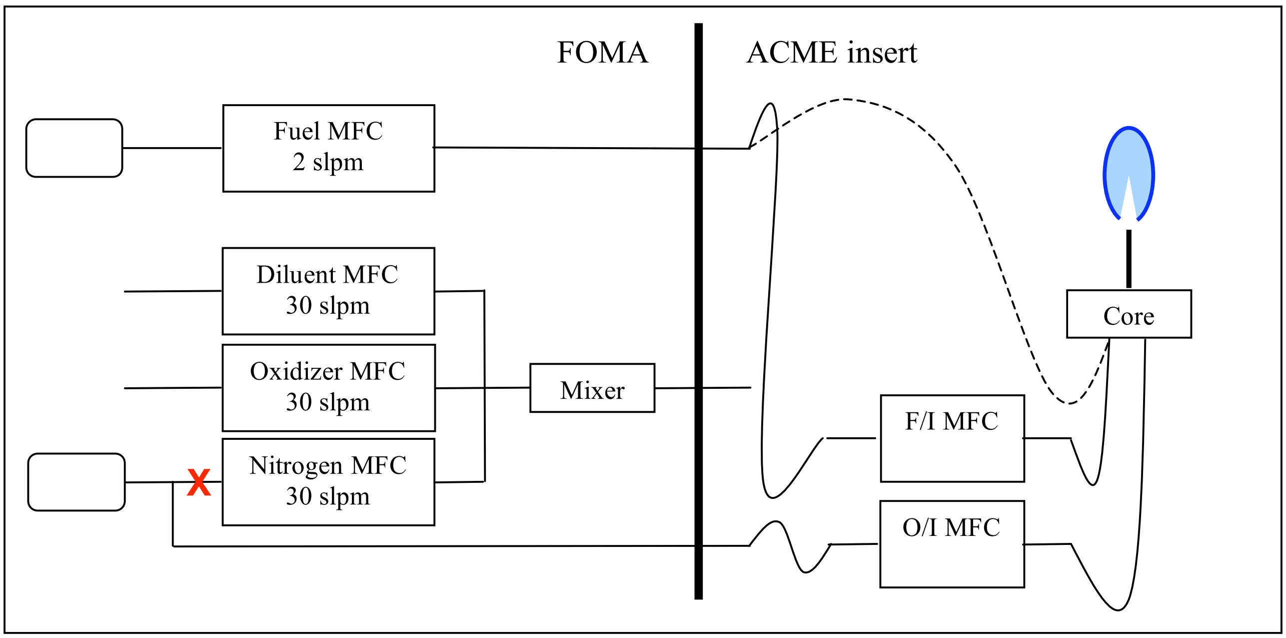


Figure 5. *Configuration A is for testing with spherical and gas-jet flames. It is applicable to all of the ACME tests that do not use the coflow burner, including all of the s-Flame tests, the Flame Design tests using a spherical burner, and the desired E-FIELD Flames with a gas-jet burner.*

Experiments	*F/I MFC*	*O/I MFC*
CLD Flame	*n/a*	*n/a*
E-FIELD Flames	*0.1 slpm*	*0.05 slpm*
Flame Design	*0.2 slpm*	*5 slpm*
s-Flame	*0.5 (or 0.02) slpm*	*2 (or 0.05) slpm*

(B) Coflow Burner Tests with Normal Flames

(B1) Fixed Oxygen Concentrations

Fuel

FOMA fuel bottle at GB2
FOMA MFC1 (2 slpm) typically driven full open for ACME control
QD11 at the chamber's interface resource ring
ACME MFC (e.g., 0.1 slpm) ***or*** *no ACME MFC (for FOMA flow control)*
core/center flow mixing plenum

Oxidizer

FOMA oxidizer bottle at GB1
FOMA MFC3 (30 slpm)
QD13 at the chamber's interface resource ring
no ACME MFC (for FOMA flow control)
coflow mixing plenum

Nitrogen (inert)

N2 supply or FOMA inert bottle at GB7
branch with no flow control
QD12 at the chamber's interface resource ring
ACME MFC (e.g., 0.05 slpm)
core/center flow mixing plenum

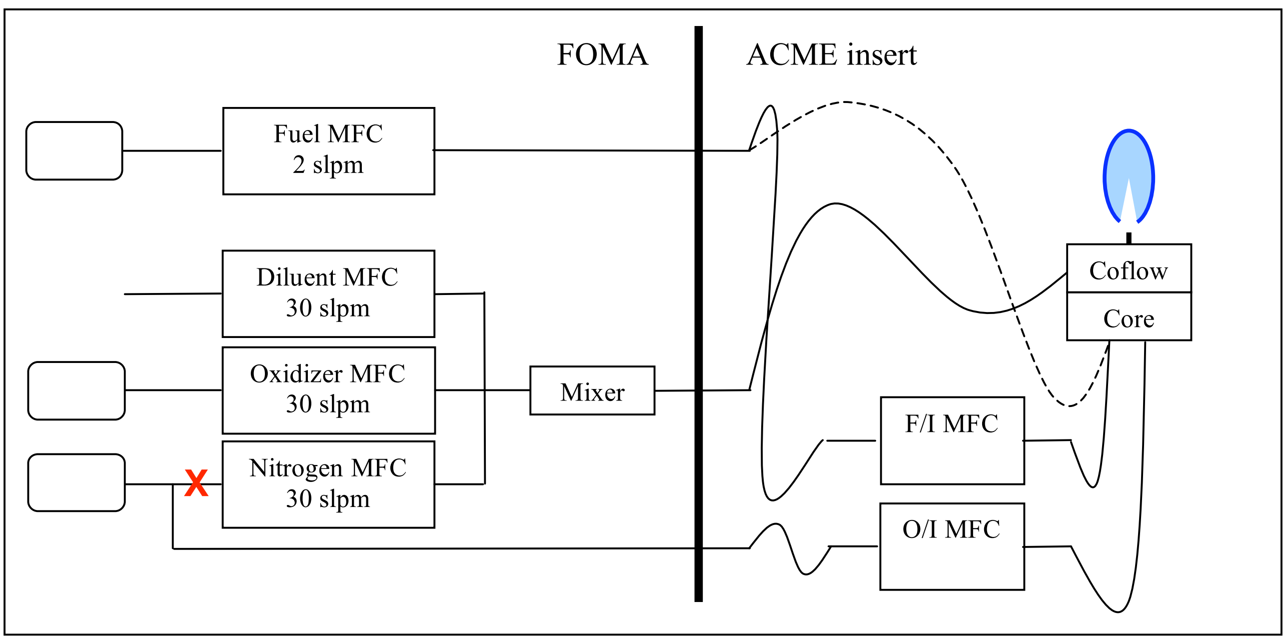


Figure 6. *Configuration is for normal coflow flame tests with a pure oxidizer coflow, and fully meets the needs of the CLD Flame experiment and the coflow tests in the E-FIELD Flames experiment. It is also appropriate for the normal coflow flame tests of the Flame Design experiment. Note that configuration B1 is an extension of A, with the addition of a FOMA controlled oxidizer coflow.*

Experiments	*F/I MFC*	*O/I MFC*
CLD Flame	*0.02 or 0.2 slpm*	*0.1 (or 0.02) slpm*
E-FIELD Flames	*0.1 slpm*	*0.05 slpm*
Flame Design	*0.2 slpm*	*2 slpm*
s-Flame	*n/a*	*n/a*

(B2) Fixed Fuel Concentrations

Fuel

FOMA fuel bottle at GB2
FOMA MFC1 (2 slpm) typically driven full open for ACME control
QD11 at the chamber's interface resource ring
ACME MFC (? slpm) ***or*** *no ACME MFC (for FOMA flow control)*
core/center flow mixing plenum

Oxidizer

FOMA oxidizer bottle at GB1
FOMA MFC3 (30 slpm)
QD13 at the chamber's interface resource ring
no ACME MFC (for FOMA flow control)
coflow mixing plenum

Nitrogen (inert)

N2 supply or FOMA inert bottle at GB7
branch with no flow control
QD12 at the chamber's interface resource ring
ACME MFC (? slpm)
coflow mixing plenum

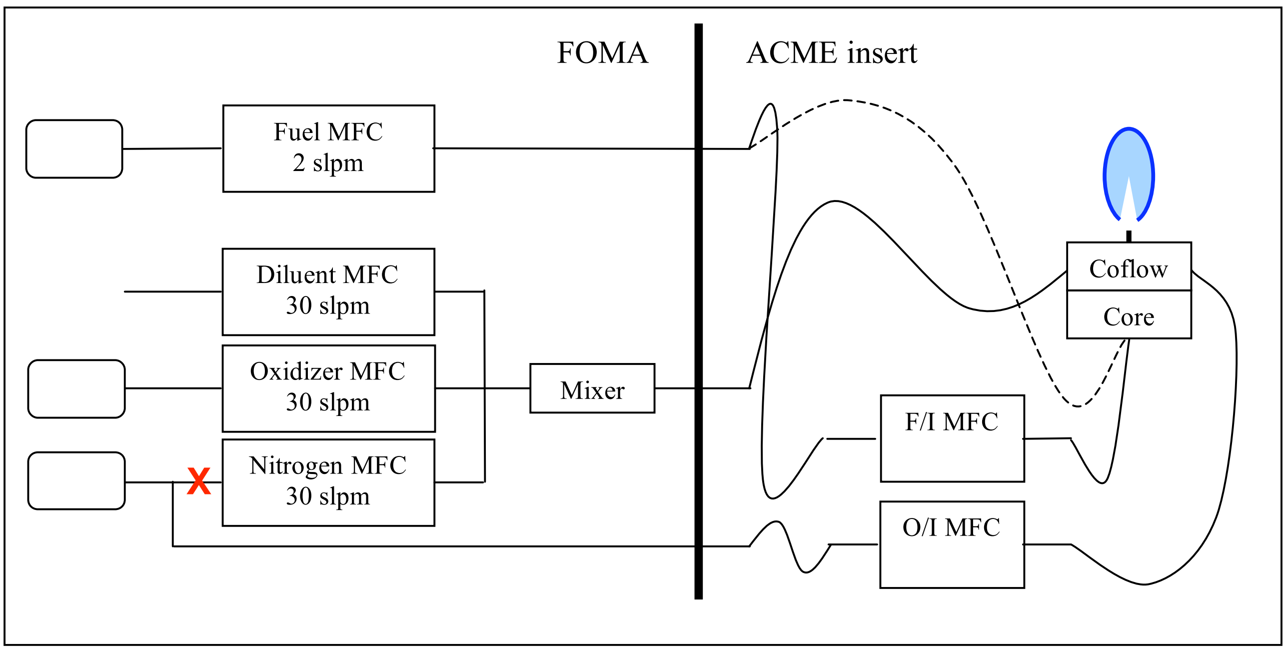


Figure 7. *Configuration B2 is for normal coflow flame testing with a pure or premixed fuel. This configuration could be used in some Flame Design tests, but the current test matrix assumes the use of a limited number of fixed oxygen concentrations (30%, 50%, and 85%) with fuel/inert mixing, as accomplished through configuration B1.*

Experiments	*F/I MFC*	*O/I MFC*
CLD Flame	*n/a*	*n/a*
E-FIELD Flames	*n/a*	*n/a*
Flame Design	*n/a - tentatively*	*n/a - tentatively*
s-Flame	*n/a*	*n/a*

(C) Coflow Burner Tests with Inverse Flames

(C1) Fixed Oxygen Concentrations

Fuel

FOMA fuel bottle at GB2
FOMA MFC1 (2 slpm)
QD11 at the chamber's interface resource ring
no ACME MFC (for FOMA flow control)
coflow mixing plenum

Oxidizer

FOMA oxidizer bottle at GB1
FOMA MFC3 (30 slpm) driven full open for ACME control
QD13 at the chamber's interface resource ring
ACME MFC (? slpm)
core/center flow mixing plenum

Nitrogen (inert)

N2 supply or FOMA inert bottle at GB7
branch with no flow control
QD12 at the chamber's interface resource ring
ACME MFC (? slpm)
coflow mixing plenum

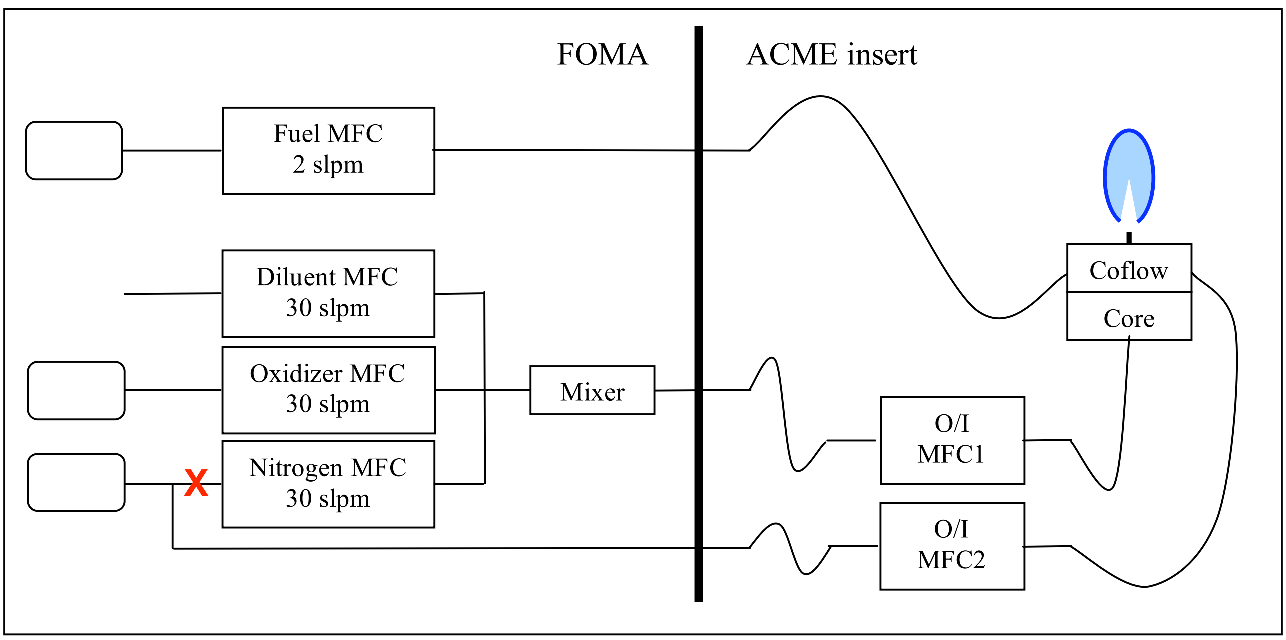


Figure 8. *Configuration C1 is for inverse coflow flame tests with a pure or premixed oxidizer. This configuration will meet the requirements of the Flame Design studies of inverse flames specified in the current test matrix.*

Experiments	*O/I MFC1*	*O/I MFC2*
CLD Flame	*n/a*	*n/a*
E-FIELD Flames	*n/a*	*n/a*
Flame Design	*2 slpm*	*15 slpm*
s-Flame	*n/a*	*n/a*

(C2) Fixed Fuel Concentrations

Fuel

FOMA fuel bottle at GB2
FOMA MFC1 (2 slpm) driven full open for ACME control
QD11 at the chamber's interface resource ring
no ACME MFC (for FOMA flow control)
coflow mixing plenum

Oxidizer

FOMA oxidizer bottle at GB1
FOMA MFC3 (30 slpm) driven full open for ACME control
QD13 at the chamber's interface resource ring
ACME MFC (? slpm)
core/center flow mixing plenum

Nitrogen (inert)

N2 supply or FOMA inert bottle at GB7
branch with no flow control
QD12 at the chamber's interface resource ring
ACME MFC (? slpm)
core/center flow mixing plenum

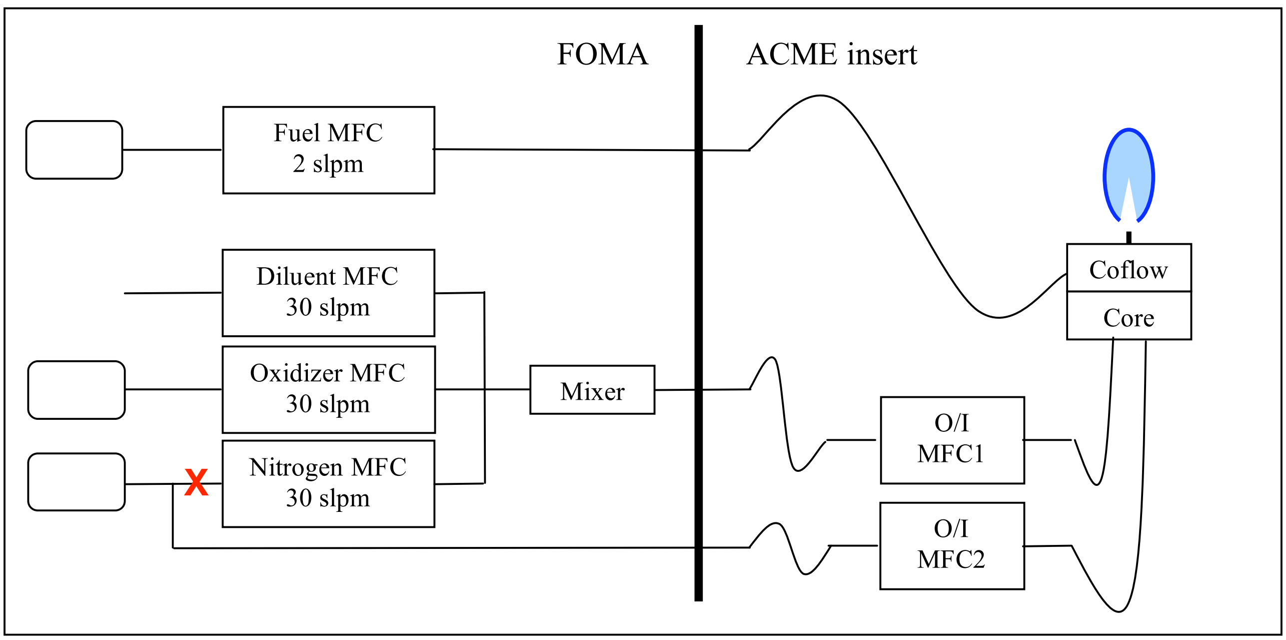


Figure 9. *Configuration C2 is for inverse coflow flame tests with a pure or premixed fuel coflow. This configuration could be used in some Flame Design tests, but the current test matrix assumes the use of a limited number of fixed oxygen concentrations (30%, 50%, and 85%) with fuel/inert mixing, as accomplished through configuration C1.*

Experiments	*O/I MFC1*	*O/I MFC2*
CLD Flame	*n/a*	*n/a*
E-FIELD Flames	*n/a*	*n/a*
Flame Design	*n/a - tentatively*	*n/a - tentatively*
s-Flame	*n/a*	*n/a*